Developmental neural models of delayed intentional behaviour

Thesis

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Jacqueline Zöllig

of Berg, SG

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and Prof. Dr. Lutz Jäncke

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If I had to live my life again I would have made a rule to read some poetry and listen to some music at least once a week; for perhaps the parts of my brain now atrophied could thus have been kept active through use.

Charles Darwin (from *Autobiography*, 1887)

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1. INTRODUCTION

Again forgotten to take out the garbage when leaving the house but you actually thought of making the phone call to the concert hall for those tickets you wanted? Either way it was your intentional behaviour that failed you in the first example but helped you to your tickets in the second one. The present thesis focuses on developmental aspects of delayed intentional behaviour – or the so-called prospective memory – by considering both failures in executing a delayed intention but also resources needed for a successful performance. The thesis begins with an introduction to the construct 'prospective memory' followed by an overview of methodological proceedings used to study this construct and their main findings. It gives then a summary of the current state of the art regarding developmental aspects of delayed intentional behaviour (chapter 1). Based on this current knowledge open questions are identified and three main research questions extracted (chapter 2). These questions are addressed in the consecutive three studies with each first stating specific predictions and their rationale in an introduction followed by a methods section. The successive results are thereafter discussed in the context of the respective study (chapter 3). Finally, in the last chapter a general discussion relates the findings to the three presented research questions and states implications as well as consequences for future studies. The thesis concludes with an outlook on a unifying model of delayed intentional behaviour (chapter 4).

1.1 Definition of terms

Already in this previous section it becomes evident that different terms are used to describe the same or a similar construct: prospective memory and delayed intentional behaviour. Whereas the former term is relatively new and seems well defined (for the first handbook see Brandimonte, Einstein, & McDaniel, 1996) the latter derives from one of the first constructs studied in psychology addressing volitional respectively intentional behaviour (e.g., Ach, 1935; Heckhausen, 1980; Kuhl, 1983; Lewin, 1926) and is much broader. The present thesis is based on research investigating the newer construct 'prospective memory'. Accordingly, the following chapter gives a brief introduction on theoretical aspects of this construct by first taking a process and then a paradigmatic view. Although it would lead too far to introduce the second construct in depth relevant findings are introduced that

complement prospective memory research in terms of expansions of the existing models and reasons for the use of a broader terminology (i.e., delayed intentional behaviour respectively delayed intentions or future intentions).

1.1.1 The construct 'prospective memory': Process view

The term 'memory' has at least two different temporal focuses whereof one centres on the realization of future plans or intentions – e.g., making a phone call to the concert hall to buy the tickets – and the other addresses events from the past including the recall or recognition of previously learned information – e.g., recall the situation when you first heard the band. This distinction has resulted in the use of the expression 'prospective memory' for the former and 'retrospective memory' for the latter (Meacham & Leiman, 1982).

This terminology has led to the supposition that prospective memory is a distinct form of memory and it has therefore often been opposed to retrospective memory. Hence, Einstein and McDaniel (1990; 1996) differentiated these two constructs by the presence of external retrieval cues – whereas the retrieval of retrospective memory is *externally prompted*, the execution of prospective memory requires the *self-initiated* retrieval of intentions. Although this distinction displays a fundamental difference between the two constructs, Ellis (1996) raised concerns that the emphasis on the involvement of memory processes – in both concept and content – might lead to the omission of other relevant cognitive processes in prospective remembering.

Accordingly, a conceptual framework was proposed to identify and include the multiple processes required to realize a future intention following four consecutive phases: (1) Intention formation, (2) Intention retention, (3) Intention initiation, and (4) Intention execution (Ellis, 1996; Kliegel, McDaniel, & Einstein, 2000). Processes required in the first phase are primarily responsible for the formation and encoding of the content of a delayed intention consisting of an action ('what'; e.g., ticket reservation), intent ('that'; e.g., decision to reserve a ticket), and retrieval context ('when'; during coffee break when the phone booth is free). The second phase consists of processes being active in maintaining the intention while being engaged in other ongoing activities (e.g., the various tasks during a normal working day). In the third phase processes are needed that support the detection of the prospective cue (e.g., seeing the vacant phone booth) during a possible performance interval when the execution of the intended action is appropriate (e.g., coffee break). And finally in the fourth phase processes are demanded that facilitate the correct

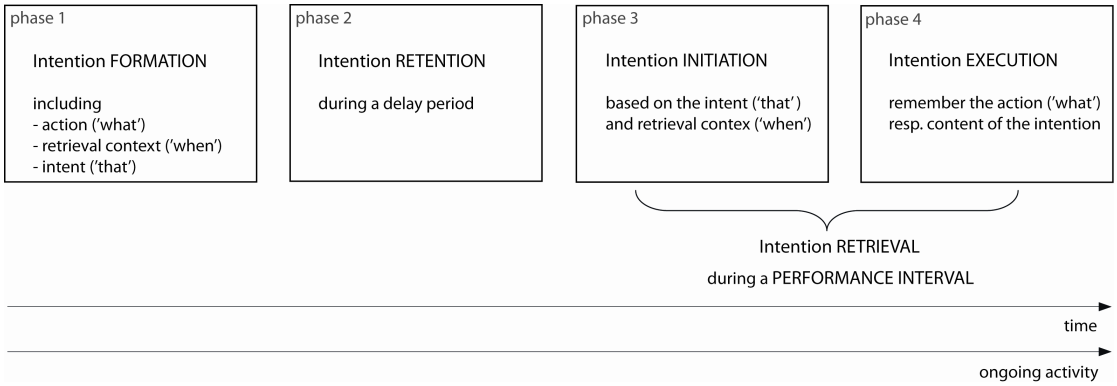


Figure 1. Prospective memory as multiphase process according to Ellis (1996) and Kliegel et al. (2002).

execution of the previously formed intention (e.g., disengaging from the coffee talk, remembering the name of the band). The examples show that processes required in the first phase are merging with the ones in the fourth phase which makes a clear assignment of the processes to one of the two phases difficult. Hence, they are often summarized under the umbrella term 'intention retrieval phase'. The different phases and the consecutive order are displayed in Figure 1.

This *multiphase model* makes it clear that the construct prospective memory relies on a multitude of processes including retrospective memory processes (e.g., encode, maintain, and retrieve the name of the band once you get through, e.g. Einstein, Holland, McDaniel, & Guynn, 1992) as well as higher order cognitive processes including planning and coordination, attention allocation, inhibition and task shifting (e.g., imagine the planning of the intention for coffee break and the multitude of events going on in this time window, e.g., Martin, Kliegel, & McDaniel, 2003; Ward, Shum, McKinlay, Baker-Tweney, & Wallace, 2005). These higher order processes belong to the construct of executive functions. There is consensus among prospective memory researchers that the cognitive resources underlying the retrospective memory aspects are separable from those that are associated with aspects of executive functions (e.g., Marsh, Hicks, Cook, Hansen, & Pallos, 2003; Maylor, Smith, Della Sala, & Logie, 2002b; Smith & Bayen, 2006; West, Bowry, & Krompinger, 2006).

Consistently, on a more general level a distinction has been made consisting of two components of a prospective memory task that – at least in part – represent the processes needed for a successful prospective memory performance: (1) a *retrospective component* referring to the encoding, maintenance, and retrieval of the action ('what' the intention

consists of) and the retrieval context ('when' the intention has to be executed) and (2) a *prospective component* compromising the maintenance of the intention itself ('that' an intention was formed in the first place, Einstein et al., 1992; Einstein & McDaniel, 1990, 1996; Ellis, 1996; Smith & Bayen, 2006). Attempts have been made to combine these two approaches and assign the two components to the multiple processes (Ellis, 1996; Kliegel et al., 2002). However, further conceptual work is needed to unify the different approaches and processes.

1.1.2 The construct 'prospective memory': Paradigmatic view

The following section describes the so-called standard-type prospective memory task but also two other paradigmatic specifications which have been distinguished in the prospective memory field – namely task setting and type of task.

The *standard-type prospective memory task* was designed to measure prospective memory in a controlled setting featuring a naturally occurring prospective memory task (Einstein & McDaniel, 1990). The underlying characteristic is the dual-task structure consisting of an ongoing activity in which the actual prospective task is embedded. This leads to the required disengagement from the ongoing task upon cue detection to perform a specific action. Typically, there is a delay between encoding and execution of the intended action and no external reminder is given. A characteristic example of such a task would be the identification of famous faces as an ongoing activity (i.e., tell the name of the person) and to make a specific response when a person is wearing eyeglasses (Rendell, McDaniel, Forbes, & Einstein, 2007).

Furthermore, depending on the nature of the ongoing task respectively the setting in which a prospective task is embedded a distinction has been made between so-called *naturalistic and laboratory-based tasks*. In the former the prospective task is part of the everyday life of participants and is thought to represent a potentially naturally occurring event – e.g., drop a postcard for the experimenter into the mailbox or making a phone call at noon the next day (e.g., Maylor, 1990; Patton & Meit, 1993). In the laboratory setting the ongoing activity as well as the prospective task is an artificial task – e.g., executing a specific action in response to a particular cue while working on a short-term memory task (Einstein & McDaniel, 1990).

In both settings the cue can either be defined as a specific event (e.g., seeing the mail box) or a specific time (e.g., at noon the next day). This distinction has led to a further differentiation between two types of tasks: *event-based and time-based prospective*

memory tasks (Einstein & McDaniel, 1990). Thus, in event-based tasks the prospective response is given to a specific external event whereas in time-based tasks the reaction should follow a specific point in time. The present thesis focuses on event-based prospective memory tasks.

1.1.3 Prospective memory as intentional behaviour

Based on the above two sections it becomes obvious that prospective memory is an 'umbrella term' (Ellis & Freeman, 2008, p. 1) that describes both processes involved in prospective remembering as well as task or paradigmatic specifics. Moreover, as described above a variety of process in different phases are involved in prospective memory which have not yet been fully described. Furthermore, the discussion of how specific intentions are selected and formed in the first place has only just started (Smith, 2008).

In this line of reasoning it might be helpful to include research in the field of motivational psychology having since early on investigated intentional behaviour (e.g., Halisch & Kuhl, 1987) and which resulted in the formulation of the the 'rubicon model of Heckhausen and Gollwitzer' (Gollwitzer, 1991; Heckhausen, 1980; Heckhausen, Gollwitzer, & Weinert, 1987). The model describes the various stages of an intention including goal intention and action plans (i.e., from wish to realization) and was used to explain individual differences in behaviour given similar abilities. The following four action phases are described (1) predecisional phase in which a goal is chosen and transformed into a goal intention, (2) preactional phase consisting of the planning of the goal pursuit, (3) actional phase in which the goal is executed, and (4) postactional phase in which the consequences and outcomes of the action are evaluated. Hence, the inclusion of findings from this field into prospective memory research might enlarge the view of processes involved in successful prospective memory including cognitive, social, and motivational aspects.

Accordingly, the findings on action plans facilitating the initiation of an action (so-called implementation intentions, e.g., Gollwitzer, 1996; Gollwitzer & Brandstaetter, 1997) have only recently been applied in prospective memory research to explain differences in performance (for an overview see Cohen & Gollwitzer, 2008). The idea behind these action plans is that planning in advance when, where and how one will complete a self assigned goal will lead to greater success. Hence, there are different reasons to use a broader terminology – as was suggested previously (Ellis, 1996; Ellis & Freeman, 2008; Smith, 2008) – and also a broader position as regards content when studying prospective

memory. In the present thesis the terms 'prospective memory', 'delayed intention', and 'future intention' are used as synonymous.

1.2 Methodological proceeding

Although there have been considerable advances in prospective memory research in the last few years (for two edited volumes see, Brandimonte et al., 1996; Kliegel, McDaniel, & Einstein, 2008b) it is still a new area of study. The traditional approach consisted of behavioural measures focusing primarily on accuracy and reaction time, whereas neurobiological underpinnings of prospective memory have essentially been absent in the first edited volume. In the meantime there has been considerable progress in identifying the neural structures involved in prospective memory by using two complimentary methodologies: functional neuroimaging methods (PET and fMRI) and event-related potentials (ERPs). Moreover, those studies have mainly focused on phase three respectively four, the retrieval of a delayed intention and only few studies have examined the behavioural and neural correlates of the formation of an intention.

The following chapter provides an overview of methods used in studying delayed intentions and states their main findings – considering behavioural and neurophysiological research (ERP, fMRI, and PET). Furthermore, findings from the two studied phases (encoding and retrieval) are separately discussed in each method section. The chapter closes by stating specific advantages of combining these methodological approaches.

1.2.1 Behavioural approach

The majority of findings in prospective memory research have operationalised delayed intentional behaviour by using different aspects of behavioural measures deriving from accuracy, reaction times, and verbal reports.

Analyses of *accuracy* on one hand allows statements about the functionality of prospective memory and characteristics of error patterns for specific groups (e.g., see Schmitter-Edgecombe & Wright, 2004, for findings on fluctuating impairments in prospective remembering in patients with mild traumatic brain injury, TBI) or following an intervention (for example by varying instructed task importance in a group of patients with Parkinson's disease, Altgassen, Zollig, Kopp, Mackinlay, & Kliegel, 2007). On the other hand analyses of *reaction times* can for instance help to make a prediction about the cognitive load experienced by different groups during the performance of a prospective

task (for example by comparing young and old adults in their 'task costs', e.g., Smith & Bayen, 2006). Finally, by using *verbal reports* strategies of performing a delayed intention including elaborateness of plans (e.g., Kliegel, Eschen, & Thone-Otto, 2004) and use of external memory aids (e.g., Hertzog, Park, & Morell, 2000) can be examined.

By considering the multiphase process of prospective memory the majority of studies has either focused on the *intention retrieval phase* or used measures that made a distinct assignment to one of the processes difficult respectively could influence different phases (e.g., external memory aids could provoke elaborate encoding and/or support retrieval processes).

Regarding the *intention formation phase* there was considerable progress in recent years. While in the first edited volume on prospective memory twelve years ago (Brandimonte et al., 1996) only one study explicitly investigated the formation and encoding of a delayed intention (Goschke & Kuhl, 1993), a sound number of studies have replicated and extended the findings stating an 'intention superiority effect' (for a recent overview see Ellis & Freeman, 2008). Furthermore there is a growing body of research investigating the impact of 'implementation intentions' for successful prospective remembering (for a recent overview see Cohen & Gollwitzer, 2008).

1.2.2 Neurophysiological approach

Only few studies are available that have targeted the neural correlates of prospective memory (for an overview see Burgess et al., 2008; West, 2008). Moreover, those studies have mainly focused on phase three respectively four, the retrieval of a delayed intention. Less than a handful of studies have so far examined the neural correlates of the formation of an intention.

Intention retrieval

Data using event-related potentials (ERPs)

Work using event-related brain potentials (ERPs) to examine the neural correlates of prospective memory during the intention retrieval (including initiation and execution) have revealed three modulations of the ERPs: N300, frontal slow wave (FSW), and prospective positivity (PP, for a recent overview see West, 2008). These ERPs have been differentially related to the prospective and retrospective components of prospective memory during intention retrieval ('that' = initiation of the action, 'what' = execution of the action).

The *N300* represents a negativity over occipito-parietal regions of the scalp and emerges between 200 and 400 ms after stimulus onset (West, Herndon, & Crewdson, 2001). The duration is rather phasic in nature (West & Ross-Munroe, 2002) but in some studies it lasts for several hundred milliseconds (West & Krompinger, 2005). The component reflects greater negativity for prospective cues than for ongoing activity trials and the amplitude is higher for prospective cues that elicit a correct prospective response (i.e., prospective hits) than for cues that fail to do so. This lead to the proposal that it is associated with processes underlying the successful detection of prospective cues (e.g., West & Krompinger, 2005; West & Ross-Munroe, 2002). Hence, it was suggested that the N300 reflects a neural correlate of the prospective component of prospective memory (West, Herndon, & Covell, 2003a).

The *FSW* reflects a sustained positivity over frontal regions of the scalp emerging approximately 400 ms after stimulus onset (West & Covell, 2001; West & Krompinger, 2005). The functional significance of this modulation is not yet clearly understood, but two possibilities are discussed. First, findings suggest that it might reflect a neural generator that coordinates the disengagement from the ongoing activity (West, Herndon, & Ross-Munroe, 2000; West & Ross-Munroe, 2002) by actively shifting the attention from one task to the other. This proposal is based on findings derived from a patient with focal frontal lesion who showed an impaired prospective memory performance when the task required an active disengagement from the ongoing task (Cockburn, 1995). A second functional significance of the FSW might be an evaluation of recovered information from memory (Einstein & McDaniel, 1996; West & Ross-Munroe, 2002). This is similar to ERP findings in retrospective memory literature associating the frontal slow wave with the activity of post-retrieval processes that use recollected information to guide task performance (Allan & Rugg, 1998).

The *prospective positivity* (PP) is typically observed between 400-1200 ms after stimulus onset and is broadly distributed over the central, parietal, and occipital regions of the scalp (West & Covell, 2001). Both the N300 and the PP are triggered by varying attributes of the prospective cue (i.e., colour, letter case, letter or word identity) and nature of the ongoing activity (i.e., semantic judgment, target discrimination, n-back, West et al., 2006; West et al., 2001; West & Krompinger, 2005; West & Wymbs, 2004). Like the N300, the prospective positivity distinguishes prospective hits from prospective misses indicating that it is associated with successful prospective memory (West & Ross-Munroe, 2002). The prospective positivity reflects two distinct components. The first is associated

with the retrieval of a prior episode from memory and is common to prospective memory and explicit episodic memory (e.g., recognition or cued-recall, West & Krompinger, 2005). The second appears to be more unique to prospective memory and may be related to post-retrieval processes that serve to coordinate the prospective and ongoing components of the task after a cue is detected and an intention is retrieved from memory (West & Krompinger, 2005). Hence, it was suggested that the prospective positivity reflects a neural correlate of the retrospective component of prospective memory (West et al., 2003a).

Data using functional neuroimaging (fMRI / PET)

Neuroimaging studies consistently reveal an involvement of the rostral and lateral prefrontal cortex, anterior cingulate as well as parietal cortex including precuneus and posterior cingulate in detecting and executing delayed intentions (Burgess, Quayle, & Frith, 2001; Burgess, Scott, & Frith, 2003; Okuda et al., 1998; Simons, Scholvinck, Gilbert, Frith, & Burgess, 2006; West, 2008). In the following section functions associated with these regions are briefly discussed by differentiating between two general activation areas: prefrontal and parietal.

Areas of the *prefrontal cortex* have been related to executive functions and there is common agreement that functionality of these processes are linked to successful prospective memory performance. This is based on findings from two directions: one considering structural abnormality in the frontal lobes in patients with a prospective memory deficit (e.g., Cockburn, 1995; Fortin, Godbout, & Braun, 2003) and the other correlating executive processes with prospective memory performance in controlled experimental studies (e.g., Kliegel et al., 2004; Knight, Titov, & Crawford, 2006; Marsh & Hicks, 1998; Salthouse, Berish, & Siedlecki, 2004). More precisely, from a functional perspective it was proposed that these regions support a cognitive control network associated with sustained attention and vigilance – particularly to visual stimuli (Burgess et al., 2001; Cabeza et al., 2003; Coull, Frith, Frackowiak, & Grasby, 1996). Consistently, Simons et al. (2006) linked activation in prefrontal regions to processes supporting cue identification respectively detection. In the endeavours to specify the functional role of prefrontal areas in prospective memory research on one subregion (Brodmann Area 10) has led to the formation of the so-called ‘gateway hypothesis’ (for an overview see, Burgess et al., 2008; Burgess, Simons, Dumontheil, & Gilbert, 2005). This hypothesis differentiates the functional contribution of the lateral and medial prefrontal cortex in prospective memory. It was supposed that the interaction of these two regions direct the flow of

information between internal and external worlds of the individual – namely between the externally presented stimulus and the internal representation of the prospective cue which was previously encoded. Hence, prefrontal areas chiefly seem to support processes associated with the prospective component of prospective memory.

Activations in the *parietal cortex* have in retrospective memory studies been associated with processes supporting the retrieval of stored mnemonic information – such as recollection, retrieval confidence, and imagery (for a recent review see, Wagner, Shannon, Kahn, & Buckner, 2005). Consistently, in prospective memory research parietal regions showed a greater activation during retrieval of the intention content (Simons et al., 2006). Hence, activation in these regions seem to support processes associated with the retrospective component of prospective memory.

Intention formation

Data using event-related potentials (ERPs)

So far, only two studies have looked at ERPs to examine the neural correlates of prospective memory during the intention formation phase (West et al., 2003a; West & Ross-Munroe, 2002). Findings revealed four modulations of the ERPs that have been shown to differentiate ongoing activity trials from intention formation trials: N2, late positivity complex (LPC), frontal slow wave (FPSW), and temporo-parietal slow wave (TPSW).

The *N2* reflects a phasic negativity over occipito-parietal regions with a peak around 300 ms. This modulation differentiated later realized and unrealized intention trials from ongoing activity trials. For analysis it was divided in an early and a late portion based on age-related differences (see chapter 1.3.1). The *LPC* represents a positivity over the parietal region of the scalp and a negativity over the lateral frontal regions with a peak around 600 ms. It was suggested by West et al. (2003a) that the LPC reflects the P3 that is typically elicited by the presentation of a low-probability attention-demanding stimulus (Donchin & Coles, 1988) and reverses polarity over the lateral frontal regions when an average reference is used (Spencer, Dien, & Donchin, 2001). Both components – the N2 and the LPC – differentiated intention formation from ongoing trials but not later realized from later unrealized intention trials. It was therefore suggested that these modulations do not reflect a neural correlate of the effectiveness of the intention formation but rather a neural response to the perceptual salience of the intention formation stimuli (West et al., 2003a; West & Ross-Munroe, 2002).

Contrariwise, the other two components (*FPSW* and *TPSW*) seemed to reflect a neural correlate of the effectiveness of intention encoding as the amplitudes were elevated for later realized intention trials compared to later unrealized trials (West et al., 2003a; West & Ross-Munroe, 2002). The *FPSW* reflects a sustained negativity over the frontal-polar region of the scalp and lasts approximately from 500-1000 ms whereas the *TPSW* represents a positivity that is detected over temporo-parietal regions of the scalp and lasts approximately from 800-1200 ms. This research is based on an effect that is commonly observed in ERP studies of retrospective memory (Sm (subsequent memory) or Dm (difference due to memory) effect, Paller, McCarthy, & Wood, 1988; Rugg, 2002). This Sm effect describes the finding that material that are later recalled or recognized elicit a greater positivity over the frontal regions compared to materials that are later forgotten. Hence, this effect was associated with elaborative processing during encoding (Donchin & Fabiani, 1991). The fact that the polarity differs between FPSW and the commonly found Sm effect was ascribed by West et al. (2003a) to differences in task conditions. This would suggest that different neural correlates support a similar process (encoding) depending on the task being a prospective or retrospective memory task (Otten & Rugg, 2001a).

Data using functional neuroimaging (fMRI)

To date, only one fMRI study has investigated encoding processes in delayed intentions (Eschen et al., 2007). The study was specifically designed to investigate the 'action superiority effect' proposed by Freeman and Ellis (2003). This effect states a better memory performance (i.e., higher retrieval rate and faster reaction time) for action words encoded for later enactment compared to those encoded for later verbal report. Consistently, the activation of regions supporting motor preparation differed between the two encoding strategies (to-be-enacted versus to-be-reported) suggesting that preparatory motor operations are active during encoding of delayed intentions requiring a future motor response. Hence, the study focused on encoding processes considering one of three aspects of intention formation – namely the content of the intention ('what' – action). The encoding of the intention itself ('that') as well as the appropriate situation ('when') was not considered. This is to be kept in mind, as it might influence the activation pattern. Furthermore, no conclusion can be drawn about elaborate encoding of specific trials within one encoding strategy as a blocked-design was used.

1.2.3 Reasons for combining these methodological approaches

By integrating findings from both behavioural and neurophysiological measures we can illuminate a specific research question from different angles and integrate respective findings to a consistent and comprehensive pattern. Some specific advantages are briefly discussed in the following.

Examine differences in performance AND in achieving a successful execution

The focus while using behavioural data has often been laid on the description of performance (i.e., impaired performance in patients with schizophrenia, e.g., Altgassen, Kliegel, Rendell, Henry, & Zollig, 2008; or in old age, e.g., Henry, MacLeod, Phillips, & Crawford, 2004). While this description of error patterns has led to the development of clinical tests and improvement of diagnostics (Thone-Otto & Walther, 2008), it can not explain how individuals manage to perform well in prospective tasks. By including neurophysiological measures and the focus on stable respectively successful performance we gain fundamental information on how correct execution of delayed intentions is achieved in different groups (i.e., associated processes and structures). This, furthermore, might be the basis for maintaining the performance and for building interventions.

Distinction of compensatory processes and dedifferentiation

Through the integration of behavioural accuracy and neural correlates a consistent conclusion can be drawn on the question of compensatory activation versus dedifferentiation processes (see for example Cabeza, Anderson, Locantore, & McIntosh, 2002 for this discussion). Whereas a higher activation in successful trials suggests compensatory processes, a higher activation in unsuccessful trials might be due to dedifferentiation processes (i.e., failure to selectively recruit specialized cortical regions in response to task demands). Thus, the fact that we can distinguish between realized and unrealized trials (respectively correct and false reactions) by considering accuracy allows the direct comparison of neural differences in these two trials respectively the neural correlates of successful performance. In neurophysiological research of retrospective encoding processes this methodological approach was called subsequent memory effect (Sm effect, e.g., Rugg, Fletcher, Frith, Frackowiak, & Dolan, 1996; Rypma & D'Esposito, 2003).

Distinguish the contribution of encoding and retrieval processes to one measured outcome

Considering the multiphase process of prospective memory a successful performance depends on the functionality of processes in all four phases (Ellis & Freeman, 2008). Similarly, an unsuccessful execution of a delayed intention might be due to incomplete encoding processes or inefficiency of retrieval processes or both. It is difficult, however, to dissociate these possible effects on encoding and retrieval using behavioural measures alone. Because by including only the behavioural outcome variable (correct, false) the differential impact of processes in the different phases contributing to this outcome can not be examined. Now, by including neurophysiological measures the separate identification of brain regions that are active during encoding and retrieval is possible (Morcom, Good, Frackowiak, & Rugg, 2003).

Investigate temporal dynamics AND neural generators of processes

The specific advantage of using electrophysiology lies in the temporal resolution allowing the examination of the time course of brain dynamics (e.g., Werkle-Bergner, Muller, Li, & Lindenberger, 2006 for a recent overview in retrospective memory research). Whereas fMRI-based research has reached some consensus about the neural network involved in prospective memory (Burgess et al., 2008; West, 2008, see also previous chapter) the aspect of time and dynamic interactions among brain regions can not be addressed with this methodology. Hence, by using ERPs the temporal dynamics and possible interactions of processes being active in one phase of a delayed intention (e.g., retrieval or encoding) can be examined.

Contrariwise, the disadvantage of EEG is the low spatial resolution and the fact that the signal is recorded at the scalp surface. Consistently, conclusions about underlying neural generators of recorded signals can not be drawn by using ERPs alone. Recent studies using ERPs failed to identify evidence for compensation (e.g., Nessler, Johnson, Bersick, & Friedman, 2006) – possibly due to slow or temporally jittered timecourse (Gutchess, Ieuji, & Federmeier, 2007) – and it was suggested that the kind of compensatory effects seen with fMRI might not be detectable using ERPs.

However, the application of a source localization method – low-resolution electromagnetic tomography (LORETA) – allows a consistent estimation for the 'inverse problem' and provides the neural generators for a defined time window in a three-dimensional intra-cerebral distribution (Pascual-Marqui, 1999, 2002; Pascual-Marqui,

Michel, & Lehmann, 1994). Furthermore, this method distinguishes the neural correlates of simultaneously active processes which might lead to component overlap in ERPs and hence to difficulties in detecting them (see Gutchess et al., 2007). Consistently, Gutchess et al. suggested that the method being able to detect compensatory activity by using ERPs holds much potential for clarifying additional regions activated in different groups or different conditions.

1.3 Developmental aspects of prospective memory

The following section is arranged in three chapters with the first summarizing developmental findings in prospective memory across the adult lifespan and the second across childhood. Both chapters outline the current state of the art by considering both research differentiating phases (mainly intention retrieval and intention formation) and processes (in the form of research distinguishing between the prospective and retrospective component). Findings are considered deriving from behavioural as well as from neurophysiological research. The chapter closes by stating specific reasons and advantages of considering a lifespan perspective.

As the present thesis focuses on event-based prospective memory tasks findings regarding time-based tasks are not explicitly summed up.

1.3.1 Developmental findings across the adult lifespan

Intention retrieval

Data using behavioural measures

The major focus regarding developmental aspects in prospective memory lay on differences between young and old adults in the *retrieval respectively execution phase* using extreme group and cross sectional designs (for an overview see Henry et al., 2004). Findings reveal an inconsistent pattern with studies reporting no differences between young and old adults or even a superior performance of the old (e.g., Maylor, 1990; Patton & Meit, 1993; Rendell & Thomson, 1993, 1999). Contrariwise, there are an increasing number of findings reporting a clear age-related reduction in prospective memory performance in old age (for a meta-analysis see Henry et al., 2004; Mantyla & Nilsson, 1997; Park, Hertzog, Kidder, Morrell, & Mayhorn, 1997; West et al., 2003a). This inconsistent findings have led to the term age prospective memory paradox (Rendell & Craik, 2000) and it was argued that it might be explained by differences in task setting.

Consistently, the meta-analysis of Henry et al. (2004) showed a clear distinction between so-called laboratory-based and naturalistic task settings. Whereas in the former a consistent age-related reduction in performance was found findings in the latter reported no age-related differences or a better performance of old adults (for a recent overview see Phillips, Henry, & Martin, 2008). So far, no consistent explanation has been found.

However, the majority of studies are laboratory-based and report a reduced performance of old adults with fewer correct reactions and longer reaction times in comparison to young adults (for a meta-analysis see Henry et al., 2004; Mantyla & Nilsson, 1997; Park et al., 1997; West & Bowry, 2005; West et al., 2003a) but also more false alarms (Einstein, McDaniel, Smith, & Shaw, 1998; Zöllig et al., 2007). Furthermore, the laboratory setting allows a controlled experimental design and has accordingly led to specific manipulations of certain aspects of prospective memory – so for example of the pro –and retrospective component. Here, evidence from studies using behavioural and mathematical modelling methodologies indicates that the effects of aging may be greater on the prospective than the retrospective component of prospective memory (Cohen, West, & Craik, 2001; Smith & Bayen, 2004; West & Craik, 2001). With some evidence indicating that age-related declines in the prospective component may result from a reduction in the likelihood that older adults engage in preparatory processing that facilitates the recognition of prospective cues (Kidder, Park, Hertzog, & Morrell, 1997; Logie, Maylor, Della Sala, & Smith, 2004; Smith & Bayen, 2006).

Data using event-related potentials (ERPs)

Consistent with the hypothesis that older adults fail to recruit controlled attentional processes that facilitate the detection of prospective cues, the amplitude of the *N300* was consistently found to be reduced in old compared to young adults (West & Bowry, 2005; West & Covell, 2001; West et al., 2003a). This is furthermore supported by data finding a selectively reduced amplitude in old adults over the right hemisphere (West et al., 2003a) where previous research have reported effects of attention (West et al., 2006; West & Wymbs, 2004). It seems therefore, that processes associated with the prospective component of prospective memory are clearly contributing to the age-related decline in realizing a delayed intention.

The effects of aging on the *frontal slow wave (FSW)* are inconsistent with two studies finding a reduced amplitude in old adults (West & Covell, 2001; West et al., 2003a) and one study reporting an elevated FSW of old compared to young adults (West &

Bowry, 2005). It was suggested, that old adults' efficiency of disengagement mechanisms in prospective memory supporting the shift from ongoing to prospective task is reduced (West et al., 2003a). This is consistent with evidence from studies reporting an age-related reduction in the efficiency of task switching (Kray & Lindenberger, 2000; Salthouse, Fristoe, McGuthry, & Hambrick, 1998).

The effects of aging on the *prospective positivity* have been somewhat mixed in previous research. One study reported a clearly reduced amplitude in old adults compared to young adults (West & Covell, 2001), whereas West et al. (2003a) found little or no effect of aging on the prospective positivity. Two factors are discussed that might explain this inconsistency. The first source of variation between the two studies was discussed to result from confounded effects of the P3 component and prospective positivity (West, Wymbs, Jakubek, & Herndon, 2003b). The second explanation suggested that although young and old adults differ in their neural recruitment of postretrieval processes the topography over parietal regions overlapped (West & Bowry, 2005). Consistently, data from this study revealed a different topography over frontal regions of the scalp and a similar over parietal regions. It seems therefore, that also the retrospective component of prospective memory contributes to the age-related decline in prospective memory across the adult lifespan.

Intention formation

Data using behavioural measures

Regarding the formation respectively the encoding of an intention there are only few studies looking at age-related differences. These differences in strategies were assessed by using the aforementioned action plans of intentional behaviour research (implementation intentions – see chapter 1.1.3). So far, findings suggest that old adults make less elaborate plans when encoding a prospective intention than young adults and that those less efficient plans are correlated with old adults' deficient performance (e.g., Kliegel et al., 2004; Kliegel et al., 2000). In addition, Kliegel, Martin, McDaniel, Einstein and Moor (2007) have recently shown that improving older adults' intention formation through the use of implementation intentions may lead to comparable prospective memory performance of young and old adults.

Data using event-related potentials (ERPs)

These findings of age-related differences in intention formation have been partly confirmed in the only available neurophysiological study investigating intention formation in young and old adults (West et al., 2003a). Whereas young adults displayed a higher amplitude in the FPSW old adults' amplitude was elevated in the TPSW. As both ERPs differentiated between later realized and later unrealized intention trials, they seem to reflect a neural correlate of the effectiveness of intention encoding. Thus suggesting that young and old adults might differ in the neural system recruited to form respectively encode intentions and in the temporal dynamic of processes.

1.3.2 Developmental findings across childhood

Intention retrieval

Data using behavioural measures

Developmental studies with a clear focus on prospective memory in children are scarce (for a recent overview see Kvavilashvili, Kyle, & Messer, 2008). Overall, roughly one dozen studies have conducted experimental research in this field (e.g., Guajardo & Best, 2000; Kerns, 2000; Kvavilashvili, Messer, & Ebdon, 2001; Martin & Kliegel, 2003; Meacham & Colombo, 1980; Winograd, 1988) and they are limited to the comparison of age groups ranging from preschool to adolescence.

Findings reveal that already very young children – in their pre-school years – exhibit some competence in executing a delayed intention (Guajardo & Best, 2000; Kliegel & Jäger, 2007; Somerville, Wellman, & Cultice, 1983). This competence further develops across childhood supposedly along with increasing skills to use external reminders to cue prospective remembering (Beal, 1988; Mantyla, Carelli, & Forman, 2007; Meacham & Colombo, 1980). Regarding the contribution of the prospective respectively the retrospective component to the development of prospective memory the evidence is inconsistent. Some findings identified an increased efficiency of strategic monitoring processes to be responsible for the improved performance of 12 year olds compared to 7 year olds and hence, an expansion in the prospective component (Ceci, Baker, & Bronfenbrenner, 1988; Kerns, 2000). Whereas other evidence point to the effectiveness of processes associated with the retrospective component for an explanation of improvements in prospective memory performance between 7 and 10 years of age (Smith, Bayen, Martin, & Metzroth, 2006).

This apparent inconsistency across studies makes it clear that the processes involved in the developmental pattern of delayed intentional behaviour across childhood remain poorly understood. Furthermore, all studies focused on the intention retrieval phase (respectively the intention initiation and execution) and none has investigated developmental patterns in the initial intention formation phase regarding the age range until young adulthood. The same scarcity of research is found in respect to potential age-related differences in neural correlates both considering the intention formation as well as the intention retrieval phase. So far, there is no study investigating developmental patterns during childhood using neurophysiological methods – whether functional neuroimaging nor electrophysiology.

1.3.3 Reasons for considering a lifespan perspective

Based on the literature and the brief overview of developmental findings in prospective memory it can be concluded that the delayed realization of intended actions undergoes significant changes across the entire lifespan. Yet, surprisingly few contributions have addressed delayed intentional behaviour including both ends of the human lifespan (for theoretical approaches see Kliegel, Mackinlay, & Jager, 2008a; Maylor, Darby, Logie, Della Sala, & Smith, 2002a). However, a broader age perspective is critical for a comprehensive understanding of development processes in prospective memory. For example, it is not yet clear whether the described developmental pattern (simulating an inverted U-shaped function of performance across the lifespan) persists when the same paradigm is applied in age groups. Another important question that still needs to be addressed is the comparability of mechanisms underlying this pattern (i.e., are there fundamental differences between processes responsible for the decline in old age and the maturation in childhood?). Whereas the first point can only be addressed by an experimental study using the same paradigm in all age groups (children, young adults, and old adults), evidence for the second point might be discussed by considering age-related changes in neural structures associated with prospective memory.

One region showing considerable changes during development is the prefrontal cortex. For this brain area there are many reports confirming a late structural development with some aspects not maturing until late adolescence or even early adulthood and a relatively early decline in old age (the latter was called the ‘frontal lobe hypothesis of aging’, see for example West, 2000). These changes were found in studies on anatomical measures such as myelination, cortical thickness, dendritic, and synaptic proliferation and

chemical characteristics (e.g., Benes, 2001; Giedd et al., 1999; Pfefferbaum et al., 1994; Raz et al., 2005; Sampaio & Truwit, 2001; Sowell et al., 2003). Consistently, age-related changes in executive functioning (which have been associated with the prefrontal cortex, e.g., Stuss, 1992) show a similar pattern with a relatively late maturation of certain functions across childhood and adolescents and a decline in old age (Kray, Eber, & Lindenberger, 2004; Zelazo, Craik, & Booth, 2004). The reported development of prospective memory performance in childhood and old age may thus results from the lack of input from frontal regions that are necessary for encoding processes, retrieval of source information, self-initiation of an action, and other executive functions. Thus, it is expected that children and old adults may partly rely on cortical networks available from other brain regions to perform a task requiring functions from frontal areas. The interesting question now is, if these two age groups recruit different strategies to compensate the reduced effectiveness.

A first evidence that children and old adults might show differential patterns derives from the report that old adults' performance in cognitive tasks might be defined not only by the decline in brain regions involved in these tasks but also their lifelong adaptations to these processes of decline (Werkle-Bergner et al., 2006). Accordingly, it was suggested that older adults might be more effective in compensating by redefining tasks to suit their own strengths than children (Kliegel et al., 2008a). Thus, it might be possible that the mechanism and processes recruited for a successful performance in old adults is more heterogeneous than during childhood.

A further evidence that children and old adults might show differential age patterns derives from the fact that other brain regions – which might be able to compensate – differ in their development-related changes. So for example the medial temporal lobe: In old age subregions of this brain area show an accelerated decline after the fifth decade (prefrontal regions show steady decline beginning in the mid-20s, e.g., Raz et al., 2005). Whereas in childhood the medial temporal lobe matures at a considerably faster rate than the prefrontal regions (e.g., Lenroot & Giedd, 2006; Raz & Rodrigue, 2006). This might suggest that children can use input from the medial temporal cortex to compensate for reduced input from frontal lobes, whereas old adults' functional status of both regions is compromised. This is in line with research reporting a specific compensatory effect in old adults consisting of the recruitment of homologous brain areas which results in a reduced asymmetry of underlying functions (the so-called HAROLD-model of aging, e.g., Cabeza, 2002).

To sum up, despite a growing body of research the above brief overview of existing studies disclose various aspects that need to be addressed for a better understanding of developmental models and aspects of delayed intentional behaviour. Among those are for example: (1) expanding the research on children and adolescents by considering the influence of different processes and including neural correlates, (2) extend the developmental view on differential process across the lifespan by including both children and old adults in the same study, (3) increasing the focus on the multiphase process of prospective memory by including the intention formation phase, and (4) using the apparent compensational processes of old adult in naturalistic settings by finding a consistent explanation for the age paradox. Part of these open questions are addressed in the present thesis and are summarized in the following three main aims respectively research questions.

2. AIM AND RESEARCH QUESTIONS

Two of the three main research questions aim at a better understanding of developmental processes by taking on a lifespan perspective. The first question addresses age-related differences in the fourth phase of prospective memory (i.e., the execution of a delayed intention) and considers the contribution of different processes (i.e., differentiation between the pro- and retrospective component). The second question investigates potential age-related differences occurring in the first phase of prospective memory (i.e., the intention formation). The third question goes a step further and engages in explanatory mechanisms for the age prospective memory paradox in a laboratory setting and possible compensation mechanisms. These three main research questions were addressed by combining different analytical approaches. While analyses of behavioural data allowed the investigation of performance data and error patterns, the application of scalp-recorded EEG including source localization with (s)LORETA provided means to conclude on differential processes and resources needed between age groups for a successful performance.

2.1 Question 1: Do we find differential age-related patterns in the realization of delayed intentions across the lifespan?

The big majority of research investigating developmental aspects focused on the realization of a delayed intention respectively on the fourth phase of prospective memory. The state of the art in this research suggests an inverted U-shaped function with performance improving from childhood to young adulthood (e.g., Guajardo & Best, 2000; Kerns, 2000) and declining from young adulthood to later adulthood (for a review see Henry et al., 2004). Explanatory approaches for this pattern include the discussion about age-related changes in the efficiency of the two components of prospective memory (i.e., pro- and retrospective component). However, results are inconsistent both for developmental effects across childhood as well as in old age. Furthermore, none of the studies has taken a lifespan perspective to investigate potential differences in processes contributing to prospective remembering. It is therefore an open question if this inverted U-shaped function results from the 'rise and fall' of the same processes across the lifespan or whether different processes contribute to patterns of development from childhood to young adulthood to later adulthood. Findings outside prospective memory literature

focusing on the maturational changes in neural correlates across childhood and again in old adults suggest that differential processes might be affected (for more information see chapter 1.3.3.). Accordingly, the first research question aims at increasing the knowledge about processes contributing to this 'rise and fall' of prospective memory by investigating three age samples: adolescents, young adults, and old adults. Thereby a paradigm was applied that allowed to determine the impact of the two principle components of prospective memory (prospective and retrospective component) on (1) the variation in the efficiency of prospective memory and (2) the extra resources needed for a successful performance.

2.2 Question 2: Do age-related differences across the lifespan occur during the successful formation of an intention?

The second research question aims at investigating the importance of the intention formation phase of prospective memory for age-related differences in executing a delayed intention. The interest in this first phase is a based on the fact that the phases are consecutive and the processes in each phase depend on the successful execution of the processes and actions in the previous phases (Ellis, 1996). Hence, in order to successfully execute a prospective task in the fourth phase, an effective encoding of the intention is required in the first phase. Conversely, age-related differences found in the execution phase might already have occurred during encoding of the intention. In accord with this reasoning, studies investigating encoding of intentions for adult age on a behavioural level demonstrated that old adults make less elaborate plans than young adults and that correlated with their deficient performance (e.g., Kliegel et al., 2004; Kliegel et al., 2000). Further evidence for age-related differences already occurring in the first phase comes from the one EEG study investigating adult age differences in neural correlates of intention formation (West et al., 2003a). So far, there is no study investigating the intention formation phase in children or considering a lifespan perspective. Therefore, the second aim was the investigation of differential age patterns in the neural correlates of the intention formation phase across the lifespan. This aim was met by first applying an even-related EEG-design (allowing the distinction between those intentions that led to a successful performance in the execution phase and those that did not) and by second including three age groups (adolescents, young adults, and old adults). Hence, the following two research questions could be addressed: (1) Do age-related differences

previously found in the intention execution phase already occur during the intention formation phase? (2) And if so, do adolescents' and old adults' neural responses not only differ compared to young adults, but also compared to each other?

2.3 Question 3: Can the familiarity with the ongoing sequence account for the age prospective memory paradox?

The present research question aimed at the evaluation of a new explanation that might account for the age prospective memory paradox. This might, furthermore, provide a possible basis for the use of the apparent compensational mechanisms of old adults in so-called naturalistic settings. So far, explanatory approaches are scare and none of them was able to consistently elucidate the paradox. Accordingly, more methodological manipulations of specific aspects of task setting and nature of task are needed to gain further insights in this research area (Phillips et al., 2008). However, in lieu of the manipulation of external factors (like motivation and memory aids) or task specifics (such as the distinctiveness of the cue or demands of the ongoing activity) the variation of another factor might play a crucial role in explaining the paradoxical findings –namely the familiarity with the sequence of ongoing events. This idea derives from the assumption that exactly this factor differs between so-called naturalistic and laboratory settings: Whereas old adults are familiar with the course of events in their daily life this sequence is completely unpredictable in the laboratory. A possible analogy might be a bus ride in two different settings. In a familiar town the stations are known and monitoring of the target destination is at a minimum level, whereas a bus ride in an unfamiliar city requires more resources in monitoring for the destination and missing the station is more probable. The demands in these two settings to successfully complete a prospective task might therefore not be the same and the performance outcome might not be directly compared. Hence, the third aim was to investigate the hypothesis that if old adults are given the chance to familiarize with the sequence of events coming up in the laboratory task and hence start with the same 'knowledge' as in naturalistic tasks they would show a better performance. This question was addressed by inventing a paradigm that allowed the learning of sequences of events and using a between-subjects design consisting of two groups of matched older adults.

3. EMPIRICAL STUDIES

In the following, three empirical studies are presented that address the three presented research questions in a consecutive order. Each study begins with an introduction stating precise predictions about findings as well as their rationale. Subsequently, methodological information including study sample, paradigm specifications, and recording and analyses of electrophysiological data are provided. The results are first individually discussed in the corresponding study section and then more globally related to the three research questions in the next chapter (General Discussion, chapter 4).

STUDY 1

3.1 Neural and behavioural correlates of retrieving delayed intentions: Differences across the lifespan[1]

3.1.1 Introduction

Prospective memory requires the formation and later realization of intentions that must be delayed for minutes, hours, or days (Brandimonte et al., 1996). Remembering to post a letter, to take medication with a meal, or to switch off the stove after cooking are all examples of prospective memory tasks. Given these examples, it is clear that prospective memory is an important and pervasive aspect of memory outside of the laboratory, and may be regarded as one of the main factors supporting the attainment and maintenance of autonomy across the lifespan (Guajardo & Best, 2000; Meacham & Colombo, 1980; Rendell & Craik, 2000). Consistent with this idea, deficits of prospective memory account for unique variance in understanding cognitive impairment associated with attention deficit/hyperactivity disorder in children (ADHD, Kliegel, Ropeter, & Mackinlay, 2006), dementia in older adults (Duchek, Balota, & Cortese, 2006; Jones, Livner, & Backman, 2006), and depression (Rude, Hertel, Jarrold, Covich, & Hedlund, 1999). Motivated by this

[1] A similar version of this chapter has been published elsewhere (Zöllig, J. et al., 2007).

evidence, the goal of the current study was to examine the neurocognitive processes underlying variation in the efficiency of prospective memory across the lifespan.

Components of prospective memory

There is typically agreement in the prospective memory literature that the realization of delayed intentions is facilitated by prospective and retrospective processing components (Guynn, McDaniel, & Einstein, 2001; McDaniel & Einstein, 1992; Simons et al., 2006). Generally, the prospective component entails processes that support the detection or recognition of prospective cues and the retrospective component entails processes that support the retrieval of an intention from memory following the recognition of a prospective cue (Einstein & McDaniel, 1996; Smith & Bayen, 2004). Evidence from studies using behavioural, mathematical modelling, and electrophysiological methodologies have been used to distinguish the processes underlying the prospective and retrospective components of prospective memory. Behavioural evidence indicates that the prospective component is more sensitive to changes in the perceptual characteristics of the cue than to the semantic relationship between the cue and intention; in contrast, the retrospective component appears to be more sensitive to variation in the semantic relationship between the cue and intention than to variation in the perceptual characteristics of the prospective cue (Cohen et al., 2001). Evidence from studies using a variety of methods has revealed that the prospective component is more sensitive to individual differences in working memory capacity (Smith & Bayen, 2005) or variation in the working memory demands of the ongoing activity (Marsh & Hicks, 1998; West et al., 2006) than the retrospective component. Together these data led to the suggestion that in many cases the prospective component is supported by attention demanding processes that serve to monitor the environment for prospective cues (Guynn, 2003; Smith, 2003); although for an alternative view see Guynn et al., 2001). The retrospective component shares many of the processes that support explicit episodic memory in recognition and cued-recall tasks that facilitate the retrieval of contextual information from long-term memory (Einstein & McDaniel, 1996; Guynn et al., 2001; Smith & Bayen, 2004; West & Krompinger, 2005).

The general division between prospective and retrospective processing components is also supported by evidence from studies examining the neural basis of prospective memory. Patients with damage to the medial temporal lobe can exhibit deficits in both prospective memory tasks and episodic memory tasks (Palmer & McDonald, 2000) and

there is some evidence indicating that the regions of the medial temporal lobe are activated by the realization of delayed intentions (Okuda et al., 1998). These findings are consistent with the idea that there is overlap between the processes underlying the retrospective component of prospective memory and forms of explicit episodic memory including recognition and cued-recall (Einstein & McDaniel, 1996; West & Krompinger, 2005). In contrast to the retrospective component, processes underlying the prospective component may be more heavily dependent on the functional integrity of the prefrontal cortex. Evidence from a number of patient studies indicates that damage to the prefrontal cortex can result in significant impairment in prospective memory in individuals who possess largely intact explicit episodic memory when measured in the form of new learning (Burgess, Veitch, de Lacy Costello, & Shallice, 2000; Cockburn, 1995; Palmer & McDonald, 2000). Converging with the patient data, studies using functional neuroimaging methods reveal that activation of anterior prefrontal cortex may be associated with strategic monitoring that facilitates the recognition of prospective cues (Burgess et al., 2001; Burgess et al., 2003; Simons et al., 2006).

Development of prospective memory

A limited number of studies have explored the development of prospective memory in childhood and adolescence (e.g. Kvavilashvili et al., 2001; Martin & Kliegel, 2003). These studies have revealed some competence in prospective memory as early as the pre-school years (Guajardo & Best, 2000; Kliegel & Jäger, 2007; Somerville et al., 1983) that continues to develop through adolescence as children become increasingly skilled at using external reminders to cue prospective remembering (Beal, 1988; Mantyla et al., 2007; Meacham & Colombo, 1980). Other evidence indicates that improvements in prospective memory between 7 to 12 years of age reflect an increase in the efficient use of strategic monitoring associated with the prospective component of prospective memory (Ceci et al., 1988; Kerns, 2000). In contrast to this evidence, other findings indicate that improvements in prospective memory between 7 and 10 years of age may arise from an increase in the efficiency of processes underlying the retrospective component of prospective memory (Smith et al., 2006). In light of this apparent inconsistency across studies, the current investigation utilized a task that allowed us to estimate the contribution of the prospective and retrospective components to improvements in prospective memory from adolescence to early adulthood.

The development of prospective memory from young adulthood to older adulthood has been investigated in a number of studies using extreme group and cross sectional designs (for an overview see Henry et al., 2004). Here, evidence from studies using behavioural and mathematical modelling methodologies indicates that the effects of aging may be greater on the prospective component than the retrospective component of prospective memory (Cohen et al., 2001; Smith & Bayen, 2004; West & Craik, 2001). With some evidence indicating that age-related declines in the prospective component may result from a reduction in the likelihood that older adults engage in preparatory processing that facilitates the recognition of prospective cues (Kidder et al., 1997; Logie et al., 2004; Smith & Bayen, 2006). There are however other findings from studies using electrophysiological methods that reveal clear differences between younger and older adults in the neural correlates of processes associated with both the prospective and retrospective components of prospective memory (West & Bowry, 2005; West et al., 2003a). Based on these data it seems that processes underlying both the prospective and retrospective components may contribute to age-related declines in prospective memory across the adult lifespan.

ERPs and prospective memory

Work using event-related brain potentials (ERPs) to examine the neural correlates of prospective memory has revealed two modulations of the ERPs that are differentially related to the prospective and retrospective components of prospective memory (i.e., N300 and prospective positivity). The *N300* reflects greater negativity for prospective cues than for ongoing activity trials that is maximal in amplitude over the occipital-parietal region of the scalp between 300-400 ms after stimulus onset (West & Covell, 2001). The N300 is greater in amplitude for prospective hits than for prospective misses leading to the suggestion that it is associated with processes underlying the detection of prospective cues (West & Ross-Munroe, 2002) or the prospective component of prospective memory. The amplitude of the N300 is reduced in older adults (West & Covell, 2001; West et al., 2003a), and this reduction appears to result from the failure of older adults to recruit controlled attentional processes that facilitate cue detection (West & Bowry, 2005). This proposal is consistent with behavioural evidence indicating that age-related declines in prospective memory in later adulthood result from a reduction in the likelihood that older adults recruit preparatory attentional processes (Smith & Bayen, 2006).

The prospective positivity is typically observed between 400-1200 ms after stimulus onset and is broadly distributed over the central, parietal, and occipital regions of the scalp (West & Covell, 2001). Like the N300, the prospective positivity distinguishes prospective hits from prospective misses indicating that it is associated with successful prospective memory (West & Ross-Munroe, 2002). The prospective positivity reflects two distinct components. The first is associated with the retrieval of a prior episode from memory and is common to prospective memory and explicit episodic memory (e.g., recognition or cued-recall, West & Krompinger, 2005). The second appears to be more unique to prospective memory and may be related to post-retrieval processes that serve to coordinate the prospective and ongoing components of the task after a cue is detected and an intention is retrieved from memory (West & Krompinger, 2005). The effects of aging on the prospective positivity have been somewhat mixed in previous research with one study revealing little effect of aging on the prospective positivity (West et al., 2003a) and two studies revealing a clear decrease in the amplitude of the prospective positivity in older adults (West & Bowry, 2005; West & Covell, 2001).

In summary, the development of prospective memory across the lifespan follows an inverted U-shaped function with prospective memory improving from childhood to young adulthood (e.g., Guajardo & Best, 2000; Kerns, 2000) and declining from young adulthood to later adulthood (Henry et al., 2004). However, it is not clear whether the inverted U-shaped function results from the 'rise and fall' of the same processes across the lifespan or whether different processes may contribute to patterns of development from childhood to young adulthood to later adulthood. The primary goal of the current study was to examine this question using behavioural and ERP methods that allowed us to distinguish between the contribution of processes underlying the prospective and retrospective components to variation in the efficiency of prospective memory across the lifespan.

In the study we tested adolescents, younger adults, and older adults in a prospective memory task that allowed us to determine whether prospective memory errors result from failures of processes underlying the prospective or retrospective components of prospective memory. The task included two types of prospective cues, one where the prospective response was to be made and one where the prospective response was to be withheld, and two prospective responses. These conditions allowed us to determine whether failures of prospective memory resulted from prospective misses (i.e., prospective cues that failed to elicit a prospective response), or confusions or false alarms (i.e., prospective cues that elicited the wrong prospective response or a prospective response at the wrong time,

respectively). ERPs were used to examine the effects of age on the neural correlates of cue detection reflected in the N300 and retrieval of the intention from memory and post-retrieval processes reflected in the prospective positivity. If age-related variation in prospective memory results from processes underlying the prospective component we expected that prospective memory errors would reflect prospective misses in adolescents and older adults relative to younger adults and that the amplitude of the N300 would be attenuated in adolescents and older adults relative to younger adults. In contrast, if age-related variation in prospective memory results from processes underlying the retrospective component we expected prospective memory errors to reflect confusions or false alarms where individuals recognized the prospective cues but made the wrong prospective response. Additionally, the amplitude of the prospective positivity was expected to differ between adolescents and older adults relative to younger adults if processes underlying the retrospective component contribute to developmental differences in prospective memory. We also explored the functional neuroanatomy of the N300 and prospective positivity using LORETA.

3.1.2 Method

Participants

Fourteen adolescents (M = 12.8, SD = 0.6 years; 7 female), 14 younger adults (M = 22.5, SD = 1.4 years; 7 female), and 14 older adults (M = 70.1, SD = 5.5 years; 7 female) participated in the study. Data of one older adult were excluded from the analyses due to a high level of artefact in the EEG. All participants were right-handed according to their score on the Edinburgh-Handedness-Test (Oldfield, 1971). They were in good health and none reported brain injuries, psycho-affective medication, drug consumption, or other diseases affecting brain functioning. All participants were native German speakers. A standard psychometric testing battery was performed to exclude participants scoring one standard deviation or more below age appropriate norms on verbal intelligence, psychomotor speed, and memory span. The young adults were students at the University of Zurich, the adolescents were recruited through newspaper advertisement, and the older adults were recruited at a lecture for senior citizens at the University of Zurich. All adolescents were high-school students in top level Swiss 6th school grade. All participants were paid 50 CHF for their participation and were provided with written and oral

descriptions of the study before written informed consent was obtained. The experiments were conducted in agreement with the declaration of Helsinki.

Materials and Procedure

The prospective memory task followed West et al. (2003a) and consisted of 1200 trials equally divided into 6 blocks. The presentation time for each trial was fixed to four seconds, independent of response times and accuracy of the response. The inter-stimulus interval was set to zero ms (i.e., there was no pause or blank screen between trials). Each block included 172 ongoing activity trials and eight prospective memory sequences consisting of an intention formation trial, a prospective inhibit trial, and a prospective execute trial (see below). There were either 6 or 12 ongoing activity trials between the intention formation trials, the prospective inhibit trials, and the prospective execute trials. The number of ongoing activity trials between the prospective memory trials was randomized across blocks and fixed across participants. There were breaks after each experimental block lasting from three to five minutes.

Ongoing task. The ongoing task consisted of a semantic relatedness judgement task. In an ongoing activity trial, two words, one above the other, were presented in lowercase letters centred on the vertical and horizontal axis of a computer monitor. The word pairs were presented in six different colours (red, green, yellow, blue, grey and magenta). The participants' task was to decide whether the two words belonged to the same (e.g., cat and dog) or a different (e.g., table and car) semantic category. They were asked to press the 'n'-key with the right index finger if the words were related and the 'm'-key with the right middle finger if the words were unrelated. Participants were told that we were interested in their verbal ability and that they should rate word pairs according to their knowledge or their intuition when uncertain.

The words were taken from the category norms for the German language (Mannhaupt, 1983; Scheithe & Bäuml, 1995) and included nouns and verbs. The word pairs were generated following the procedure of West et al. (2003a). Accordingly, words from 50 categories excluding names of persons, cities, states, colleges, universities, and members of clergy were combined to have the same number of vowels and approximately the same number of consonants. Each word appeared twice over the course of the task (i.e., once in a related and once in an unrelated pair). The related word pairs were from the same category, whereas the unrelated word pairs were formed by randomly re-pairing words across categories.

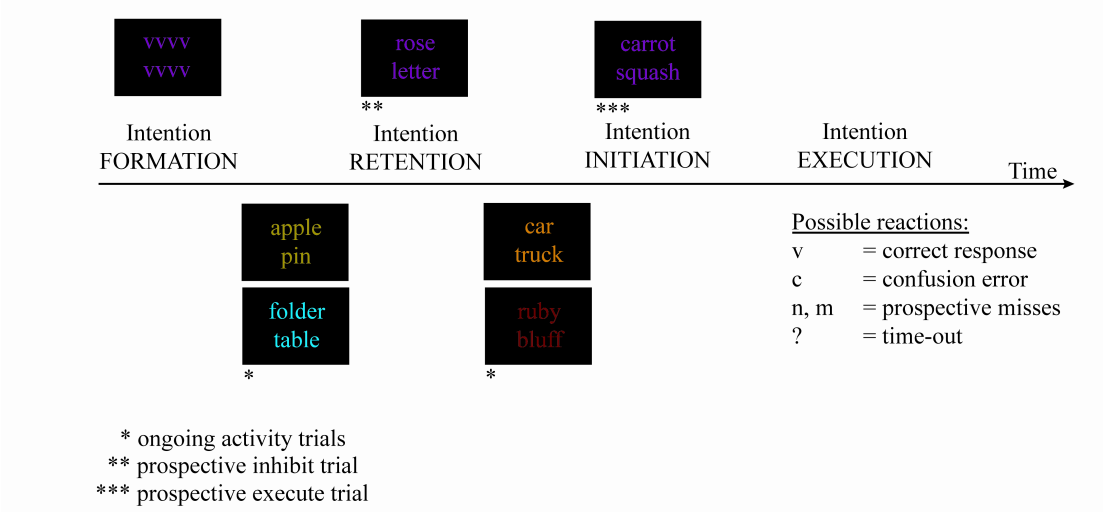


Figure 2. Illustration of the prospective memory paradigm used in the present study. Displayed is one prospective memory sequence consisting of an intention formation, a prospective inhibit and a prospective execute trial. In between these trials a varying number of ongoing activity trials must be executed. (Each trial was displayed for four seconds with no pause or blank screen between trials.)

Prospective memory task. On intention formation trials in lieu of a word pair, one of two possible letter strings ('cccc' or 'vvvv') were presented either in grey or magenta. The participants were instructed to press the corresponding button on the keyboard ('c'-key with the left middle finger and the 'v'-key with the left index finger) and to remember the colour of the letter and the letter itself. Hence, they were to form the intention to press the target key when a word pair was presented in the target colour. Extending West et al.'s (2003a) procedure we included prospective inhibit trials. Prospective inhibit trials represented the first occurrence of a word pair in the target colour after the intention formation trial. For these trials, participants were to notice the prospective cue, but were required to make a semantic judgment and, therefore, to postpone the prospective response. The prospective inhibit trials allowed us to examine the frequency of false alarms for these trials that provided an index of the efficiency of the retrospective component of prospective memory. Prospective execute trials represented the second time a word pair appeared in the prospective colour. For these trials the participants were to make the prospective response.

One prospective memory sequence is portrayed in Figure 2. In this sequence, participants encode and retain one of two possible prospective cues (here: the colour magenta) as well as one of two possible prospective actions (press the key "v"). This

constitutes the intention formation phase. When, after several ongoing activity trials, a word-pair appeared in the previously encoded target colour (e.g., magenta), the participant was supposed to notice this event, but to postpone the prospective response. After, several more ongoing activity trials a second word-pair appeared in the target colour reflecting the prospective execute trial (e.g., magenta) the prospective response had to be initiated and executed (pressing the key "v").

Before the experimental blocks, participants performed two practice blocks, each repeatable until the task was fully understood. The first block followed the instructions for the semantic categorization task and included 63 ongoing activity trials. The second block started after the prospective memory instructions were explained and consisted of 54 ongoing activity trials, and three prospective memory sequences. Participants were encouraged to ask questions during and after the practice blocks to ensure that they understood the instructions before the experimental blocks began.

Recording and analysis of electrophysiological data

Recording. The electroencephalogram (EEG) was continually recorded while participants performed the task. The EEG was amplified with a BrainAmpMR (Brain Products GmbH), digitized at 500 Hz, and recorded with a 16 bit A/D converter. During recording, a low pass filter (100 Hz) was applied, both the notch filter and high pass filters were off (BrainVision Recorder Software). The EEG was recorded from an array of 32 Ag/AgCl scalp electrodes which were placed according to the 10-20 system being sewn into an EasyCap or affixed to the skin with an adhesive patch. During recording inter-electrode impedances were maintained below 10 kΩ and all electrodes were referenced to electrode FCz. Vertical and horizontal eye movements were recorded with electrodes placed below the right and left eyes.

Processing. For data analysis, all electrodes were re-referenced to an average reference as suggested in the guidelines published by the Society for Psychophysiological Research (Picton et al., 2000). The recorded EEG was bandpass-filtered (0.1-30 Hz, time constant 1.59155s, 48 dB/oct). ERP analysis epochs were extracted off-line and included a 200 ms of pre-stimulus baseline and 1200 ms of post-stimulus activity. Ocular artefacts associated with blinks, as well as additional eye movements and articulated muscular artefacts were corrected using independent component analysis (ICA) software (http://www.puk.unibe.ch/tk2/tk.htm). This is a publicly available freeware for the VisionAnalyzer software (Brainproducts GmbH) which separates the mixture of

independent EEG signals into 30 factors (corresponding to the number of electrodes used) by conducting a component analysis. Jung et al. (1998) demonstrate that the unwanted artefacts will be contained in one or more components that can be removed and the artefact free EEG reconstructed from the remaining components. To identify the ocular components we compared the timing and topographical distribution of the artefacts in the EEG against that of the independent components. Following ocular correction, trials contaminated by remaining artefacts were rejected with the Raw Data Inspector (Vision Analyzer software, Brainproducts GmbH). ERPs were averaged for the following artefact free trials: (1) Ongoing activity trials: ongoing trials immediately preceding prospective execute trials (adolescents: M = 45.50, SD = 1.95, range = 40-48; younger adults: M = 47.36, SD = 0.93, range = 45-48; older adults: M = 44.38, SD = 3.52, range = 36-48) and ongoing trials immediately preceding prospective inhibit trials (adolescents: M = 45.93, SD = 2.09, range = 41-48; younger adults: M = 47.57, SD = 0.85, range = 45-48; older adults: M = 44.62, SD = 3.10, range = 36-47), (2) prospective inhibit trials: prospective inhibit trials that elicited a semantic judgment (adolescents: M = 38.36, SD = 3.86, range = 31-47; younger adults: M = 45.07, SD = 2.30, range = 41-48; older adults: M = 37.69, SD = 6.82, range = 21-46), (3) prospective execute trials: prospective execute trials that elicited a correct prospective response (adolescents: M = 39.29, SD = 3.65, range = 36-46; younger adults: M = 42.36, SD = 3.75, range = 34-46; older adults: M = 32.38, SD = 6.98, range = 19-43). ERPs were not averaged for errors given the relatively low number of these trials.

Analysis of mean amplitude. Differences in mean amplitude between groups and conditions were examined in two epochs where the N300 and prospective positivity are typically observed (West et al., 2003a; West & Krompinger, 2005; West & Ross-Munroe, 2002). For both ERP components we used the semi-automatic peak detection algorithm in the VisionAnalyzer software (Brainproducts GmbH). That is, the peak was detected automatically following specified criteria and then manually adjusted as needed. The N300 represented the maximum negative voltage between 200 and 400 ms and the prospective positivity represented the maximum positive voltage between 600 and 800 ms. The amplitude and latency of the N300 and prospective positivity were saved for the analyses. The selection of electrodes characterizing the N300 and the prospective positivity was based on findings from previous studies (West et al., 2003a; West & Krompinger, 2005; West & Ross-Munroe, 2002). The amplitude of the N300 was quantified at 5 electrodes

(O1, Oz, O2, P7, P8) and the amplitude of the prospective positivity was quantified at 6 electrodes (CP3, P3, CPz, Pz, CP4, P4).

Partial Least Squares (PLS) Analysis. The data matrix for the PLS analyses contained subjects and conditions in the rows, and ERP amplitudes for all time points and channels, except for the four occular electrodes, in the columns (0 - 1200 ms, at each electrode). The input data matrix for the analyses was obtained by mean-centering the columns of the ERP data matrix with respect to the grand mean. The averages within task were thus expressed as deviations around zero. Singular value decomposition (SVD) was then performed on these matrices to identify the structure of the latent variables. Three outputs were derived from the SVD that were used to interpret the relationships between ERP amplitude and task design. The first was a vector of singular values, which represents the unweighted magnitude of each latent variable and can be used to calculate the proportion of the cross-block covariance matrix (i.e., the percentage of task-related variance) attributable to each latent variable. The second and third outputs contain the structure of the latent variables and are orthogonal pairs of vectors (saliencies). One vector defines the design saliencies or design scores representing contrasts between group and task conditions across the latent variables. The other vector represents the electrode saliencies that characterize the temporal and spatial expression of the latent variable across the scalp.

The significance of the latent variables singular values was determined using a permutation test that provided an exact probability of observing the singular value by chance (e.g., $p < .001$). The empirical distribution for the permutation test was formed by drawing 500 random samples with replacement from the group x subject x condition data matrix. The singular value decomposition was performed on each random sample with the structure of the latent variables maintained across samples (i.e., the ordering of the contrast expressed in the latent variables was preserved across samples). The exact probability of obtaining the observing singular values by chance was determined by comparing this to the rank of a given singular value against those from the permutation distribution. The stability of the ERP saliencies at each time point and location in space was established through bootstrap resampling (200 replications) that provides a standard error. The ratio of the salience to its bootstrapped standard error is approximately equal to a z-score; therefore, bootstrap ratios greater than 2.5 can be taken to indicate stable saliencies or points that differ from zero (Matlab code to perform the PLS analyses can be obtained at www.rotman-baycrest.on.ca).

LORETA analysis. Low-resolution electromagnetic tomography (LORETA) was performed on the basis of the scalp-electrode electric potential distribution (Pascual-Marqui, 1999, 2002; Pascual-Marqui et al., 1994) to localize differential neural recruitment between groups and conditions. LORETA was used to estimate the three-dimensional intra-cerebral current density distribution in 2394 voxels with a grid resolution of 7 mm and a voxel volume of 0.343 cm^3. The evaluated ERPs were subjected to a LORETA analysis. The obtained images were compared on a voxel-wise basis for inter-group differences between adolescents and younger adults and between older adults and younger adults in ongoing activity trials, prospective inhibit trials, and prospective execute trials. Two time frames of interest were defined reflecting the N300 and the parietal positivity based on the mean latencies plus / minus one standard deviation. Thus the time of interest ranged for the N300 from 236 to 292 ms and for the prospective positivity from 641 to 709. The statistical comparisons were conducted using t-tests for independent samples corrected for multiple comparisons (Nichols & Holmes, 2002). These patterns of descriptive p-values were plotted in statistical probability maps (SPM). LORETA values were transformed logarithmically to achieve normal distribution. In addition, on the basis of the individual LORETA files for each subject containing the two time frames of interest, a subject-wise normalization procedure was performed. This transformation multiplies for each individual every single voxel's activity by the inverse of the total LORETA activity over all voxels and all time frames for this subject and serves to avoid a potential confound between the direct between-group comparison and the general group differences (i.e., the results from comparing adolescents with younger adults with the fact that adolescents as a group display larger amplitudes).

3.1.3 Results

Results focus on age differences in performance on the prospective memory tasks and age-related differences in neural recruitment for successful prospective remembering. Effect size is reported as eta-squared (η^2) or Cohen's *d* (Cohen, 1969). If a normal distribution could be assumed, statistical tests were performed using the multivariate *F* ratio (MANOVA). Post-hoc Tukey tests qualified the results in case of a significant main effect of age. The Greenhouse-Geisser correction was conducted if sphericity could not be assumed and epsilon (ε) is reported as a value of correction. If a normal distribution and/or variance homogeneity could not be assumed, non-parametric tests were applied using the Mann-Whitney U and Kruskal-Wallis χ^2.

Behavioural data

Response accuracy and inferential statistics for the effect of age group on ongoing activity trials, prospective inhibit trials, and prospective execute trials are presented in Table 1. For the ongoing activity trials adolescents performed more poorly than younger adults or older adults and there was no difference between the later two groups. The null effect between younger and older adults is consistent with data from previous studies using the semantic judgment task as the ongoing activity (West & Craik, 1999). The data for prospective execute trials were separated into 'correct' responses, 'confusions' when the wrong prospective response was made, 'misses' when an ongoing activity response was made, and 'time-outs'. Correct responses clearly reveal the anticipated inverted U-shaped function with performance increasing from adolescents to younger adults and decreasing from younger to older adults. Examination of the error data reveals that different processes may have contributed to variation in performance between adolescents and younger adults

Table 1. Mean accuracy for adolescents (Ado), young adults (YAd), and old adults (OAd) presented at proportions.

		Age			Main Effect		d
		Ado	YAd	OAd			
OA correct	*M*	.70	.84	.82	18.21**	a, b	1.34
	SD	.07	.046	.073			
PI correct	*M*	.88	.96	.88	6.54*	a, c	0.58
	SD	.055	.038	.096			
PI false alarms	*M*	.056	.028	.063	*5.05*°	a°, c	0.26
	SD	.046	.029	.046			
PI time-outs	*M*	.064	.010	.054	*11.89***	a	0.69
	SD	.046	.014	.074			
PE correct	*M*	.841	.906	.715	13.26**	a, b, c	1.05
	SD	.066	.076	.142			
PE confusions	*M*	.040	.017	.049	*6.96**	a, c	0.37
	SD	.032	.023	.051			
PE misses	*M*	.103	.068	.199	*11.97***	b, c	0.69
	SD	.051	.058	.120			
PE time-outs	*M*	.016	.09	.037	*6.67**	c	0.36
	SD	.017	.013	.038			

Inferential statistics for the main effect of age are presented as the F-ratio or χ^2 (italics). Significant differences in the paired contrast are indicated in the following way: a = Ado vs YAd, b = Ad vs OAd, c = YAd vs OAd. (OA = ongoing activity, PI = prospective inhibit trials, PE = prospective execute trials). * $p < .05$, ** $p < .01$, ° $p < .1$

and between younger adults and older adults (Table 1). Adolescents and older adults made more confusion errors than younger adults indicating that the retrospective component of prospective memory was more efficient in younger adults than in adolescents and older adults. Consistent with this finding, adolescents and older adults also tended to commit more false alarms on prospective inhibit trials than younger adults (this was significant for older adults, $p < .05$, and marginal for adolescents, $p < .1$). Older adults had 2 to 3 times more prospective misses than adolescents ($p < .01$) or younger adults ($p < .001$) leading to the suggestion that the prospective component of prospective memory was compromised in later adulthood.

The mean response time data for adolescents, younger adults, and older adults for ongoing activity trials, prospective inhibit trials, and prospective execute trials are presented in Table 2. The statistical analysis compared response times in a 3 (age) x 3 (trial) repeated-measures ANOVA. In this analysis the main effect of age was significant, with response time decreasing from adolescents to younger adults ($p < .01$) and increasing from younger adults to older adults ($p < .01$), adolescents and old adults did not differ significantly. The main effect of trial was also significant, with response time increasing from prospective execute trials to ongoing activity trials ($p < .001$) and from ongoing activity trials to prospective inhibit trials ($p < .001$). The age x trial interaction was significant. Paired comparisons (ongoing vs prospective inhibit; ongoing vs prospective execute) performed for every age group separately were significant for all comparisons and age groups ($p < .01$, see Table 2, column "paired contrasts"). However, there were differences in the effect sizes revealing a smaller difference in reaction times between

Table 2. Mean response time (in ms) for adolescents (Ado), young adults (YAd), and old adults (OAd).

		Trial			Age effect F-value (η^2)	Trial effect F-value (η^2)	Interaction F-value (η^2)	Paired contrasts
		OAc	PIc	PEc				
Ad	*M*	2048	2310	1317	7.65** (0.28)	251.45*** (0.87)	2.98* (0.13)	a (d = 0.73) b (d = 2.38)
	SD	393	323	221				
YAd	*M*	1669	1942	1033				a (d = 0.99) b (d = 2.60)
	SD	280	275	207				
OAd	*M*	1851	2212	1444				a (d = 1.34) b (d = 1.25)
	SD	299	216	350				

Significant differences in the paired contrast are indicated in the following way: a = OAc vs PIc, b = OAc vs PEc; with "d" as effect size. (OA = ongoing activity, PI = prospective inhibit trials, PE = prospective execute trials, c = correct). *$p < .05$, ** $p < .01$, ***$p < .001$

ongoing trials and prospective execute trials for older adults compared to adolescents and young adults. This might indicate that the intention was not as accessible in older adults as in the other two age groups (West & Craik, 1999). Additionally, the effect size for the difference in reaction times between ongoing trials and prospective inhibit trials seems somewhat greater for old adults compared to adolescents and young adults.

In summary, response accuracy and response time for prospective execute trials suggest improvements in performance from adolescents to younger adults and declines in performance from younger adults to older adults. Furthermore, analyses of the pattern of errors lead to the suggestion that somewhat different processes may underlie gains in prospective memory from adolescents to young adulthood and declines in prospective memory from young adulthood to later adulthood.

Electrophysiological data

Differences in mean voltage. The grandaveraged ERPs portraying the N300 and the prospective positivity at midline electrodes are displayed in Figure 3 and the topography of these modulations is portrayed in Figure 4. Age differences in the neural correlates of prospective remembering were examined by comparing the ERPs elicited by correct responses for prospective execute trials and prospective inhibit trials, and for ongoing activity trials preceding the prospective execute trials. The results from the 3 (age) x 3 (trial) repeated measures MANOVA including five electrodes for the *N300* and six electrodes for the prospective positivity revealed the same results as the hemisphere-specific analyses reported in the text.

The amplitude of the *N300* was quantified as the peak negative voltage between 200 and 400 ms in a 3 (age) x 3 (condition) x 2 (hemisphere: P7-O1, P8-O2) repeated measures MANOVA. The main effect of condition was significant, $F(2,76) = 15.71$, $p < .001$, $\eta^2 = 0.30$, reflecting greater negativity for prospective execute trials than for prospective inhibit trials ($p < .05$) and ongoing activity trials ($p < .001$). Amplitude was highest in adolescents and lowest in old adults, although the main effect of age was not significant, $F(2,38) < 1$, $\eta^2 = 0.04$. The only other relevant effect to be significant was the age x condition x hemisphere interaction (Figure 5), $F(4, 76) = 4.21$ ($\varepsilon = .65$), $p < .01$, $\eta^2 = 0.18$. Post-hoc analyses of this interaction (comparing prospective execute trials vs ongoing trials and prospective inhibit trials vs ongoing trials) revealed that the amplitude of the N300 (defined as the difference between prospective trials and ongoing trials) was similar across the three groups for the prospective execute trials, $F < 1.00$, $\eta^2 = .01$; and

was somewhat greater for adolescents and older adults than younger adults for prospective inhibit trials, $F(2,38) = 3.12$, $p < .05$, $\eta^2 = .14$. Paired comparisons revealed a significant difference between adolescents and younger adults ($p < .05$) and a trend in the comparison of older adults and younger adults ($p < .1$), adolescents and old adults did not differ significantly.

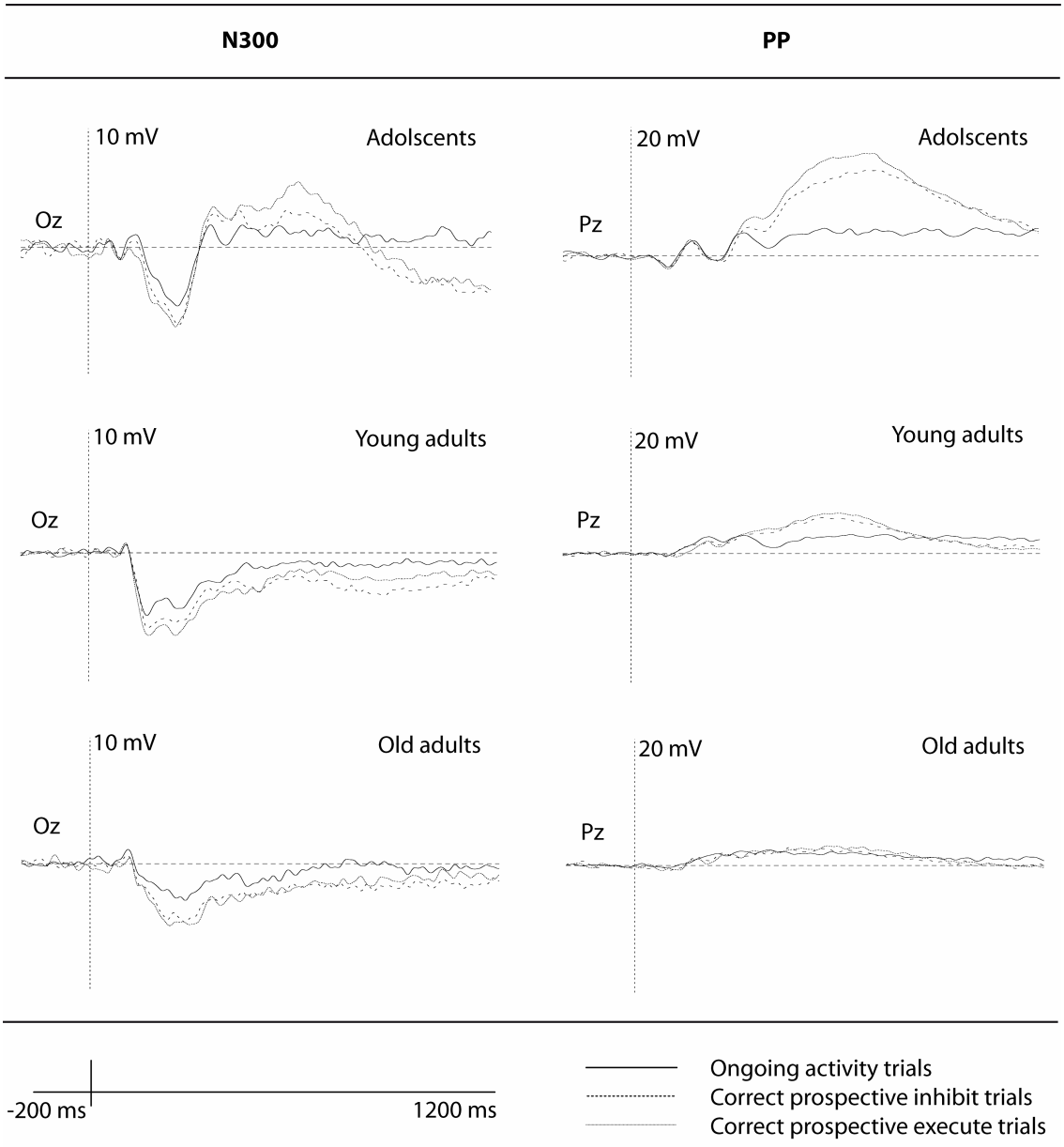


Figure 3. Grand-averaged event-related brain potentials at selected electrodes demonstrating the N300 and the prospective positivity for ongoing activity, correct prospective inhibit, and correct prospective execute trials in all three age groups. The arrows mark the relevant modulation for each electrode.

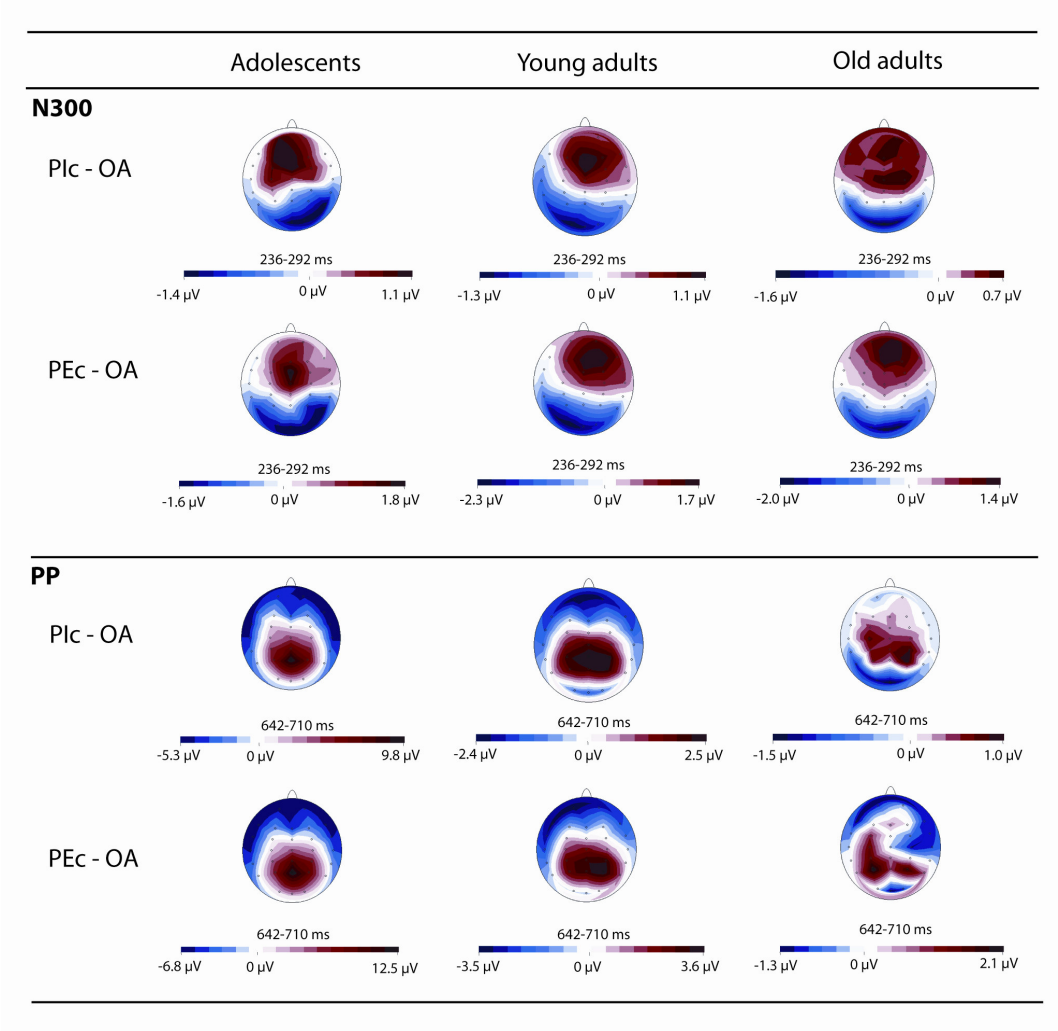


Figure 4. Topographical maps of adolescents (Ado), young adults (YAd), and old adults (OAd) representing differences between correct prospective inhibit trials (PIc) and ongoing activity trails (OA) and between correct prospective execute trials (PEc) and ongoing activity trails (OA) during the time windows that were used for analyses of the N300 and the prospective positivity. Note the different scaling to illustrate the topographical distribution.

The amplitude of the *prospective positivity* was quantified as the peak voltage between 600 and 800 ms in a 3 (age) x 3 (condition) x 2 (hemisphere: CP3-P3, CP4-P4) repeated measures MANOVA. The main effect of condition was significant, $F(2, 76) = 76.75$ ($\varepsilon = .64$), $p < .0.001$, $\eta^2 = 0.67$, with positivity decreasing from prospective execute to prospective inhibit trials ($p < .01$) to ongoing activity trials ($p < .01$). The main effect of age was significant, $F(2, 38) = 20.96$, $p < .001$, $\eta^2 = 0.52$, with amplitude decreasing from adolescents to younger adults to older adults. Post-hoc analyses revealed greater amplitude in adolescents compared to younger adults and older adults (p's $< .001$). The age x condition interaction was also significant, $F(4, 76) = 13.65$ ($\varepsilon = .64$), $p < .0.001$, $\eta^2 = 0.42$, as was the age x condition x hemisphere interaction, $F(4, 76) = 4.41$ ($\varepsilon = .81$), $p < .01$, $\eta^2 =$

0.18. This interaction reflected the decrease in the amplitude of the prospective positivity from adolescents to younger adults to older adults that was greater over the right than left hemisphere (p's < .001; η^2 = .47 over the right hemisphere; η^2 = .36 over the left hemisphere).

In summary, analyses of mean voltage revealed that the amplitude of the N300 elicited by prospective execute trials was similar across the three groups and that the amplitude of this modulation was larger for adolescents and older adults than for younger adults for prospective inhibit trials. These analyses also revealed that the amplitude of the prospective positivity decreased from adolescents to younger adults to older adults. The lack of an effect of age on the amplitude of the N300 for prospective execute trials was surprising given previous research revealing a reduction in the amplitude of this modulation in later adulthood. The reason for this null effect was examined further in the PLS analysis that allowed us to examine possible differences in amplitude across the three groups during the epoch of the N300 across all electrodes.

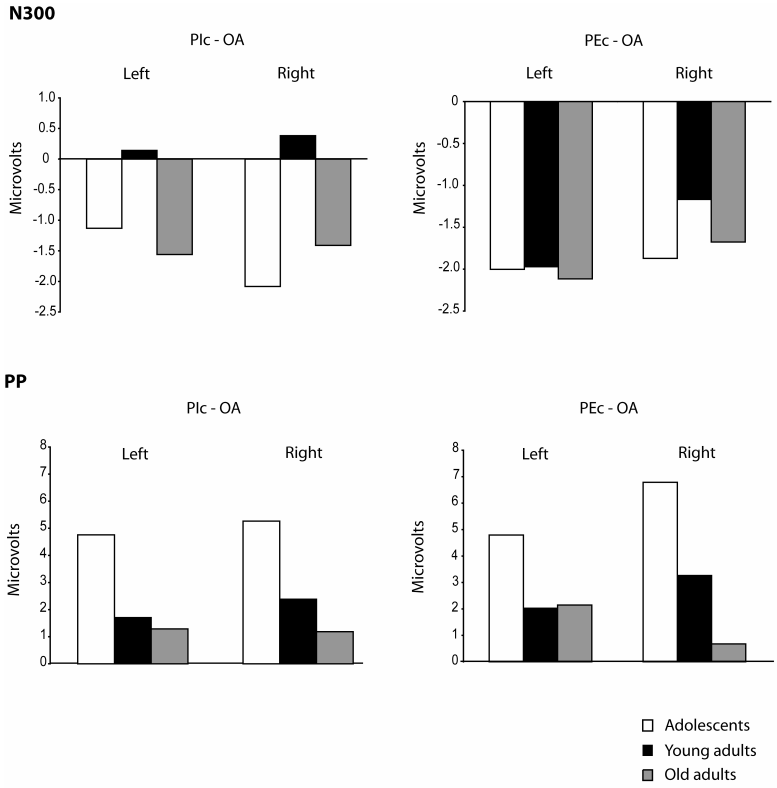


Figure 5. Difference in mean voltage portraying the age x condition interactions for the N300 and the prospective positivity over the left and the right hemisphere for every age group.

PLS Analysis. The behavioural data revealed the expected age differences in response accuracy for both prospective execute cues and prospective inhibit cues. Analyses of error data (missed prospective cues, confusion errors, and false alarms) reveal that different processes may have contributed to failures of prospective memory in adolescents and older adults. In an effort to examine the possible expression of these different processes in the ERP data, we performed a PLS analysis that included data for the three groups at all but the ocular electrode locations for the entire analyzed epoch (0-1200 ms) for ongoing activity trials preceding prospective inhibit and execute trials and for prospective inhibit and execute trials. The inclusion of the ongoing activity before prospective inhibit trials was limited to the PLS analysis as in a MANOVA they do not differ from the ongoing before execute trials. The PLS analysis has been used successfully in previous studies of the effects of aging on prospective memory to identify those modulations of the ERPs that are both commonly and uniquely expressed in younger and older adults (West & Bowry, 2005).

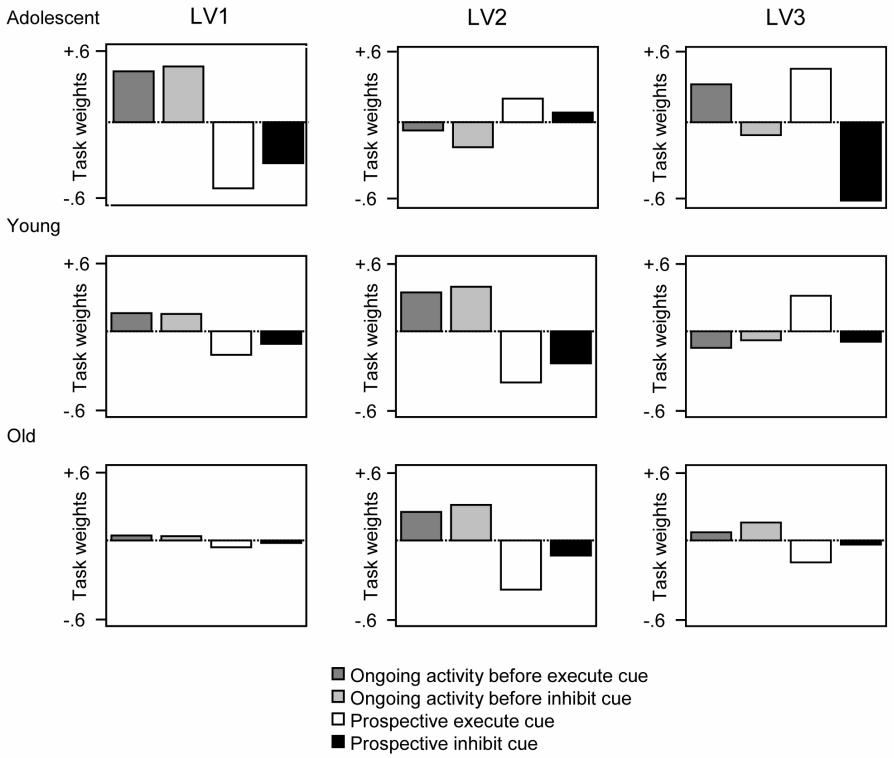


Figure 6. Design scores from the PLS analysis for adolescents, young adults, and older adults for the first three latent variables expressing the ERP correlates of prospective memory. LV1 reveals a linear decrease from adolescents to old adults; LV2 reveals a contrast that distinguishes adolescents from young and old adults and is similar in the later two groups; LV3 reveals a contrast that primarily reflects differences between prospective execute and prospective inhibit cues in adolescents.

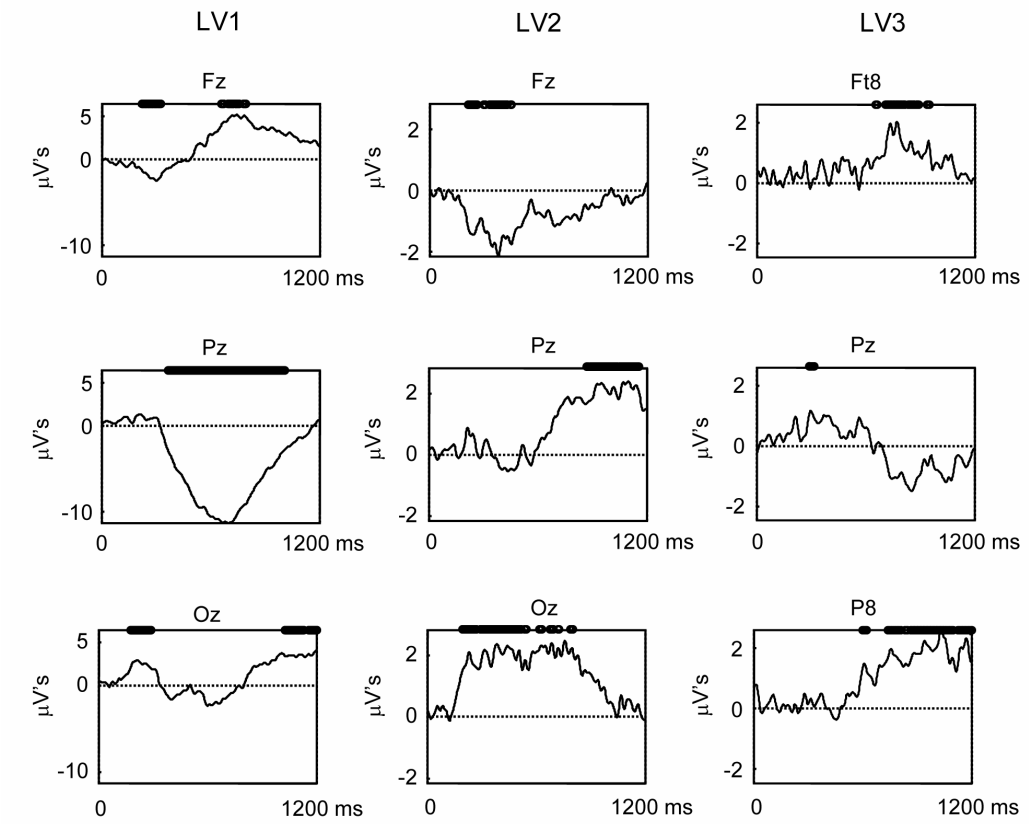


Figure 7. Electrode saliences for select electrodes from the PLS analysis for the first three latent variables over the frontal, parietal, and posterior regions of the scalp. LV1 appears to capture the N300 over the occipital and frontal regions and the prospective positivity over the parietal region. LV2 captures a longer lasting modulation over occipital and frontal regions and a later modulation over the parietal region. LV3 captures a sustained modulation beginning at around 600 ms over the right hemisphere that extends from the frontal-temporal to the lateral parietal regions of the scalp.

The PLS analysis revealed three significant latent variables ($p < .001$, $p < .004$, $p < .03$) that accounted for 79.86%, 7.42%, and 5.09% of the crossblock covariance, respectively. The design scores for the first latent variable revealed a contrast of ongoing activity trials with prospective inhibit and execute trials (Figure 6). The magnitude of the design scores for this latent variable decreased from adolescents to younger adults to older adults, being very close to zero in the older adults. The electrode saliences for the first latent variable revealed a phasic effect over the occipital-parietal and frontal regions of the scalp between 200-400 ms that reflects the expression of the N300 and a later, longer-lasting, modulation beginning at around 400 ms extending from the central and parietal regions that reflects the expression of the prospective positivity (Figure 7). The second

latent variable reflected a contrast of ongoing activity trials with prospective cue trials, with the pattern of design scores differing across the groups. In the younger and older adults the design scores were positive for ongoing activity trials and negative for prospective cue trials. This pattern was reversed in adolescents. Furthermore, this latent variable appears to be more strongly expressed for prospective execute cues than for prospective inhibit cues. The electrode saliences for this latent variable reflected a modulation over the occipital-parietal and frontal regions beginning at around 200 ms and a second modulation extending from the right central and parietal regions beginning at around 700 ms. The expression of the third latent variable also differed across the three groups. In adolescents, this latent variable primarily reflected a contrast of prospective inhibit cues with prospective execute cues. In younger adults, this pattern was also present although it was clearly attenuated. In older adults, the design scores again contrasted prospective cues with ongoing activity trials. The electrode saliences for the third latent variable reflected a transient modulation between roughly 300-400 ms and a sustained modulation beginning at around 600 ms over the right hemisphere and extending from the parietal to the frontal temporal regions. To sum up, the results of this analysis reveal two distinct patterns of age-related differences: (1) the first latent variable revealed a monotonic decrease in the magnitude of the design scores from adolescents to older adults and (2) the second and third latent variables revealed qualitative differences in the pattern of design scores across the three groups.

LORETA analysis. Source localization was performed to investigate age-related differences in neural recruitment associated with successful prospective remembering that might be reflected in variation in the pattern of design scores across the three groups in the PLS analysis. The source localization for younger adults provided a baseline for the paired comparisons, as in this group the underlying neural generators are assumed to be fully developed. The statistical probability maps from the LORETA analyses are displayed in Figure 8, local maxima of inter-group differences in the three-dimensional current density distribution for ongoing activity, prospective inhibit, and prospective execute trials are shown for the two components N300 and prospective positivity. Table 3 summarizes the brain regions that demonstrated differential activation across the groups and includes the X, Y, Z-Talairach coordinates and the *t*-value at the local maxima.

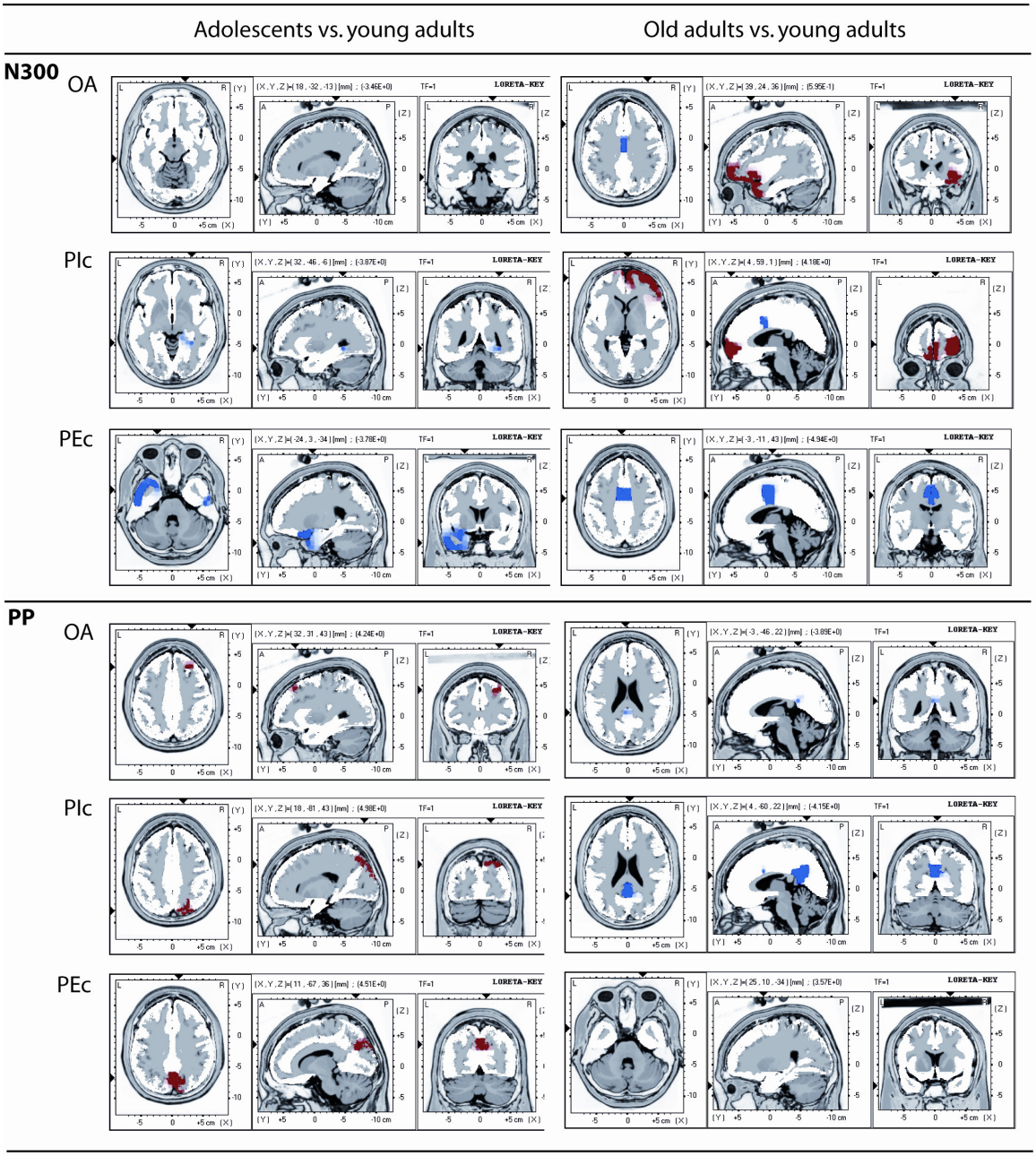


Figure 8. Statistical probability maps (SPM) of the source localization with LORETA for differences between adolescents / young adults and old adults / young adults. Results are significant at the $p < .05$ level (blue colour = significantly lower current density, red colour = higher current density).

Table 3. Local maxima in current density differences between adolescents (Ado) and young adults (YAd), and between old adults (OAd) and young adults calculated with LORETA.

Trial	Comparison	Brain region	HS	Talairach coordinat			$t_{X, Y, Z}$
				X	Y	Z	
OA							
N300	Ado vs. YAd	Parahippocampal gyrus (BA 35)	R	18	-32	-10	-3.97
	OAd vs. YAd	Superior temporal gyrus (BA 38) Middle temporal gyrus (BA 20, 21) Inferior frontal gyrus (BA 47) Middle frontal gyrus (BA 10, 11)	R	32	15	-42	3.92*
		Cingulate gyrus (BA 24, 23)	M	3	-15	43	-3.92*
PP	Ado vs. YAd	Middle frontal gyrus (BA 8, 9)	R	27	31	37	3.96*
	OAd vs. YAd	Posterior cingulate (BA 29, 30)	M	-3	-43	20	-3.96*
PIc							
N300	Ado vs. YAd	Parahippocampal gyrus (BA 36) Fusiform gyrus (BA 37)	R	32	-46	-6	-3.90*
	OAd vs. YAd	Medial/superior frontal gyrus (BA 10, 11) Inferior frontal gyrus (BA 44, 47)	R	4	66	-13	4.00*
		Cingulate gyrus (BA 24, 32) Medial frontal gyrus (BA 6)	M, R	4	1	30	-4.00*
PP	Ado vs. YAd	Precuneus (BA 7, 19, 31) Cuneus (BA 18)	R	31	-81	40	4.09*
	OAd vs. YAd	Posterior cingulate (BA 23, 29, 30) Cingulate gyrus (BA 31)	M	12	-46	5	-4.00*
PEc							
N300	Ado vs. YAd	Inferior temporal gyrus (BA 20) Middle temporal gyrus (BA 21, 38) Uncus (BA 36, 38)	L	-59	-7	-29	-3.87*
	OAd vs. YAd	Cingulate gyrus (BA 24, 23, 33) Medial frontal gyrus (BA 6, 32) Paracentral Lobule (BA 31)	M	4	-4	43	-4.59**
		Paracentral Lobule (BA 5, 6, 31) Cingular Gyrus (BA 23, 31)	M	-3	-33	46	4.63**
PP	Ado vs. YAd	Precuneus (BA 7, 31) Cuneus (BA 18, 19)	M, R	4	-67	36	4.04*
	OAd vs. YAd	Uncus (BA 38)	R	25	10	-34	4.01

OA = ongoing activity, PI = prospective inhibit trials, PE = prospective execute trials; BA = Brodmann area. * $p < .05$, ** $p < .01$

N300 time frame. Ongoing activity trials: The activity of adolescents and younger adults did not differ significantly. In older adults, the activity of the cingulate gyrus was bilaterally reduced and was elevated in the middle and superior temporal gyrus as well as the middle and inferior frontal gyrus in the right hemisphere compared to young adults. *Prospective inhibit trials:* The activation of the parahippocampal gyrus and the fusiform gyrus in the left hemisphere was reduced in adolescents compared to younger adults. Older adults had significantly greater activation in the right medial, superior, and inferior frontal gyrus than young adults. The cingulate gyrus and parts of the medial frontal gyrus of the right hemisphere showed a reduction in activity in older adults compared to younger adults. *Prospective execute trials:* Adolescents had reduced activation in the right inferior and middle temporal gyrus as well as the uncus compared to younger adults. The activity of older adults was reduced in the cingulate gyrus, the medial frontal gyrus, and the paracentral lobule.

Prospective positivity time frame. Ongoing activity trials: Adolescents demonstrated greater activation in the middle frontal gyrus of the right hemisphere compared to younger adults. The activation of the posterior cingulate gyrus was attenuated in old adults compared to younger adults. *Prospective inhibit trials:* The activation of the right precuneus and cuneus was reduced in adolescents compared to younger adults. In older adults activation of the posterior cingulate as well as the cingulate gyrus was reduced compared to younger adults. *Prospective execute trials:* The right and medial precuneus and cuneus revealed greater activation in adolescents compared to younger adults. The pattern of activation in old adults and young adults did not differ significantly. To sum up, the LORETA analyses revealed different patterns of neural recruitment in adolescents and older adults in comparison to younger adults in the time frames of both the N300 and the prospective positivity.

3.1.4 Discussion

The current study sought to examine the locus of age-related variation in prospective memory from adolescents to later adulthood and was guided by the general conceptual framework wherein the realization of delayed intentions is supported by prospective and retrospective components. Prior research led to the hypothesis that somewhat different processes might contribute to developmental differences observed from childhood to young adulthood and then from young adulthood to later adulthood (Guajardo & Best, 2000; West & Craik, 2001). To test this idea we utilized a prospective memory paradigm

that allowed us to distinguish the influence of processes associated with the prospective and retrospective components on task performance. Analyses of the behavioural and ERP data support the conclusion that somewhat different processes contribute to the 'rise and fall' of prospective memory across the lifespan.

The response accuracy data for the prospective execute trials revealed the inverted U-shaped function that has been observed in other studies of lifespan developmental effects on prospective memory (Kliegel & Jäger, 2007). Further analyses of the complete pattern of errors for prospective execute and prospective inhibit trials lead to the suggestion that differences between adolescents, younger adults, and older adults arise from processes associated with both the prospective and retrospective components of prospective memory. The number of confusion errors for prospective execute trials and false alarms for prospective inhibit trials was elevated in adolescents and older adults relative to younger adults. These data may be taken to indicate that processes underlying the retrospective component of prospective memory were not fully developed in adolescents (Guajardo & Best, 2000; King, 2005, July; Smith et al., 2006) and were compromised in older adults. This conclusion is generally consistent with a large literature examining developmental effects on explicit episodic memory. The decline in the efficiency of processes underlying the retrospective component of prospective memory is however inconsistent with recent evidence published by Smith and Bayen (2006) where age-related differences in later adulthood for memory processes underlying prospective memory were not observed. Given these and the current data, it seems that additional work is required in order to gain a more complete understanding of the conditions under which age-related differences in prospective memory in later adulthood reflect a decrease in the efficiency of the retrospective component.

Misses on prospective execute trials revealed a different pattern of age-related variation being much greater for older adults than for adolescents or younger adults. The elevated number of misses for prospective execute trials in older adults is consistent with evidence from previous research (West & Craik, 2001). Together these data seem to suggest that processes associated with the prospective component of prospective memory may be functionally intact by the time individuals reach adolescents and are compromised in later adulthood.

The electrophysiological data largely converge with the behavioural data in revealing differential patterns of neural recruitment in adolescents, younger adults, and older adults. Analysis of the mean voltage data revealed that there was little difference

across the three age groups in the amplitude of the N300 for prospective execute trials; in contrast, for prospective inhibit trials the N300 was elicited in adolescents and older adults but not younger adults. This pattern of data may indicate that adolescents and older adults were monitoring for the first occurrence of the prospective cues in a way that younger adults were not. This observation that may partially account for the elevated numbers of false alarms for prospective inhibit trials for adolescents and older adults relative to younger adults.

The absence of age-related differences between younger adults and older adults in the amplitude of the N300 was surprising given previous research that has consistently revealed an attenuation of this modulation in older adults (West & Bowry, 2005; West & Covell, 2001; West et al., 2003a). However, the results of the PLS analysis provide some insight into this discrepancy as both the first and second latent variables revealed stable electrode saliences during the epoch of the N300. Importantly, the magnitude of the design scores for the first latent variable were greater for younger adults than older adults, while the magnitude of the design scores was similar for younger and older adults for the second latent variable. This finding is consistent with prior evidence indicating that multiple processes that are more or less sensitive to the effects of aging in later adulthood contribute to generation of the N300 (West & Bowry, 2005). Specifically, West and Bowry found that aging had a negative impact of attentional processes that support the detection of prospective cues and had little effect on non-attentional processes that influence cue detection. The result of the PLS analysis also revealed that the expression of the N300 was associated with different latent variables in adolescents and older adults indicating that age-related variation in prospective memory is unlikely to result from the 'rise and fall' of a unitary or monolithic processes across the lifespan.

Analysis of the mean amplitude data also revealed that the amplitude of the prospective positivity was substantially greater in adolescents than in younger adults and was attenuated in older adults relative to younger adults (West et al., 2003a). This finding is interesting within the context of the behavioural data that reveal roughly similar elevations in the number of confusion errors for prospective execute trials and false alarms for prospective inhibit trials that was interpreted as reflecting the non-optimal functioning of the retrospective component in adolescents and older adults relative to younger adults. The results of the PLS analysis may again provide some insight into what initially appears to be a discrepancy between the behavioural and ERP data. Recall that in this analysis both the first and second latent variables revealed stable electrodes saliences over the

parietal region of the scalp during the time course of the prospective positivity. However, there were pronounced differences in the magnitude of the design scores between adolescents and older adults across these two latent variables. Where the first latent variable revealed a monotonic decrease in the magnitude of the design scores from adolescents to older adults with the design scores being close to zero in older adults. In contrast, the second latent variable revealed a different pattern of design scores between adolescents and younger and older adults. Together these finding may support the hypothesis that developmental differences in prospective memory from adolescents to young adulthood and from young adulthood to later adulthood reflect differential recruitment of the neurocognitive processes underlying the retrospective component of prospective memory rather than reflecting the 'rise and fall' of a unitary process over the lifespan.

The idea that age-related variation across the three groups reflects differences in neural recruitment between adolescents and older adults was supported by the results of the LORETA analysis. For the time frame of the N300 old adults had significantly greater activation in the right medial, superior, and inferior frontal gyrus in correct prospective inhibit trials than young adults. A similar pattern of greater activation was found in ongoing activity trials (right inferior and medial frontal gyrus). These findings are in line with previous studies using fMRI suggesting greater recruitment of right lateral frontal regions in conditions where no cue appeared and when cues were presented indicating some form of anticipatory processing (Burgess et al., 2001; Simons et al., 2006). As this activation occurred in the phase of cue detection, older adults, may recruit more resources to compare the current stimulus with the encoded representation of the prospective cue. These differences in frontal activation for ongoing activity trials and prospective inhibit trials were not found in adolescents. Furthermore, older adults showed a bilateral reduction in activity in the cingulate gyrus and medial frontal gyrus compared to young adults in all three conditions. This could reflect a reduction in preparation and readiness for actions (Cunnington, Windischberger, Robinson, & Moser, 2006), which is in line with recent findings suggesting an age-related decline in the recruitment of attentional processes that facilitate cue detection (Smith & Bayen, 2004, 2006; West & Bowry, 2005).

For the *time frame of the prospective positivity,* adolescents displayed greater activation in the precuneus and cuneus regions of the right hemisphere compared to young adults for both prospective inhibit trials and prospective execute trials. In the memory literature the precuneus is often thought to play a role in visual imagery (for a review see

Fletcher, Frith, & Rugg, 1997). It has been suggested that in prospective remembering the role of the precuneus lies in the maintenance of the prospective response (Burgess et al., 2001; den Ouden, Frith, Frith, & Blakemore, 2005). Our results, therefore, imply that adolescents might have to rely more on resources associated with the imagining and maintaining of the required response than young adults to successfully perform the prospective memory task. This is in line with behavioural findings suggesting a reduction in the efficiency of adolescents in maintaining the prospective response. This interpretation matches previous studies suggesting that some networks are not yet fully developed in children/young adolescents and that they therefore must rely on the recruitment of other networks from different brain regions to perform the task (see for example Segalowitz & Davies, 2004). It has been suggested that these developing regions are localized in the prefrontal cortex. However, the LORETA analyses did not find any differences in activation in prefrontal regions between adolescents and young adults. Nonetheless, the results from the PLS and the topographical maps suggest that there might be differences in frontal regions between adolescent and young adults not detected by the LORETA analyses. There were no significant differences between younger adults and older adults for prospective execute trials. On one hand, this suggests that aging may have relatively little effect on the prospective positivity (West et al., 2003a). On the other hand, significant bilateral differences between young adults and old adults were found in the posterior cingulate and cingulate gyrus in prospective inhibit trials with older adults having reduced activity. Burgess, Veitch, de Lacy Costello, and Shallice (2000) also found regions of the posterior cingulate to be involved in both prospective and retrospective components of multi-tasking. Previous findings have linked these areas with functions related to retrieval of stored mnemonic information (for a review see Wagner et al., 2005). Therefore, our findings lead to the suggestion that older adults compared to younger adults may be less efficient in retrieving or 'refreshing' the prospective response in prospective inhibit trials, whereas for prospective execute trials they seem to use the same regions and networks as do younger adults. This interpretation is in line with behavioural findings suggesting an impairment in the retrospective component of prospective memory in older adults.

Limitations and future directions

From a methodological perspective, ongoing task performance has to be discussed as potential caveat to the behavioural data. Specifically, if different age groups are tested using the same paradigm, it is difficult to equate task demands between groups.

Consistently with previous findings (West et al., 2003a), accuracy in ongoing activity trials did not differ between younger adults and older adults. Still, the accuracy of adolescents in ongoing activity trials was lower than that of the other two groups. One reason for this could simply be that adolescents used different semantic categories than younger adults. This would not affect our interpretation, because the ongoing task would therefore be comparable in its attentional demands across all three age groups. Secondly, it is possible that due to age differences in semantic knowledge the ongoing activity task was more difficult for adolescents than younger and older adults. However, we explicitly addressed this issue by using instructions that there was no right or wrong response for the ongoing task. Participants were instructed to guess when a word or its category was not known. Nonetheless, one could still argue that the ongoing activity required a greater amount of resources for adolescents to perform the task, which in turn may have left them fewer resources for the prospective task. However, it seems unlikely that adolescents did require more resources for the ongoing activity task as the LORETA analysis did not reveal any differences in the activation pattern of adolescents and younger adults for the ongoing activity trials. Another possible limitation of our study is the duration of the experiment that may have led to an interaction between age and fatigue. However, we provided participants with several breaks in the course of the experiment and windows were opened as often as possible. Moreover, statistical analysis of behavioural data over blocks revealed no decline in the accuracy in the end blocks for adolescents.

A further possible limitation for the interpretation of electrophysiological results arises from the repetition of prospective cues with 48 prospective memory sequences overall. It is possible that the first few cues do not trigger the same processes as the last cues and that different neural processes are involved in different phases of the experimental procedure. However, only further research using within-subjects analysis over blocks with a large number of participants will allow one to examine individual differences in prospective memory across task performance.

Conclusion

This study combined behavioural and ERP methods to provide new insights into the processes underlying age-related variation in prospective memory across the lifespan. The behavioural data revealed that processes associated with the retrospective component of prospective memory were less efficient in adolescents and older adults relative to younger adults. Additionally, processes associated with the prospective component of prospective

memory were less efficient in older adults relative to adolescents and younger adults. The ERP data revealed differences in the pattern of neural recruitment across the three groups reflecting age-related variation in both the N300 and prospective positivity. Together the behavioural and electrophysiological data support the hypothesis that somewhat different processes may contribute to the 'rise and fall' of prospective memory from childhood to later adulthood.

STUDY 2

3.2 Forming intentions successfully: Neural correlates across the lifespan

3.2.1 Introduction

Forming an intention such as to shut down the mobile phone before entering the concert hall or to take out the pizza from the oven after 20 minutes is part of the concept of prospective memory. It represents a pervasive real-world memory task that is regarded to be associated with most of everyday memory problems across the entire lifespan (see the two edited volumes on this topic for comprehensive overviews Brandimonte et al., 1996; Kliegel et al., 2008b). Generally, in the course of prospective memory performance five phases have been distinguished: (1) formation and encoding of the intention, (2) retention interval during which the ongoing task is performed, (3) performance interval, (4) initiation and execution of the intended action, and (5) evaluation of outcome (Ellis, 1996). Each phase requires different cognitive processes that eventually lead to the successful delayed realization of the original intention (Ellis & Freeman, 2008).

Surprisingly few studies are available that have targeted the neural correlates of prospective memory (for an overview see West, 2008). Moreover, those studies have mainly focused on phase four, the execution of a delayed intention (e.g. Burgess et al., 2001; Burgess et al., 2003; Okuda et al., 2007; Okuda et al., 1998; Simons et al., 2006; Zöllig et al., 2007). Less than a handful of studies have so far examined the neural correlates of the formation of an intention (i.e. Eschen et al., 2007; West et al., 2003a; West & Ross-Munroe, 2002) and none of those has looked at age differences across the lifespan. From a conceptual standpoint this is remarkable because age differences in the delayed realization of an intention are likely to be associated with age differences occurring during intention formation. The phases in the process of prospective remembering are consecutive and progress in each phase is likely to depend on the successful execution of the processes and actions required in the previous phases. Hence, to successfully execute a prospective task in the fourth phase, an effective encoding of the intention is required in the first phase. Therefore, the aim of the present paper was to

examine the neural correlates associated with the successful formation of a delayed intention and to compare those across three age groups, i.e., adolescents, young adults, and old adults. With this approach the following research questions were addressed: (1) Do age-related differences previously found in the intention execution phase already occur during the intention formation phase? (2) And if so, do adolescents' and old adults' neural responses not only differ compared to young adults but also compared to each other?

The rationale for expecting age-related differences in neural correlates during the formation of an intention rests on two main lines of reasoning. The first line of reasoning is based on findings from the *prospective memory literature* exploring the role of efficient intention formation on adult age differences in prospective memory performance. Those studies have repeatedly demonstrated that old adults make less elaborate plans when encoding a prospective intention than young adults and that those less efficient plans are correlated with old adults' deficient performance (e.g., Kliegel et al., 2000; Kliegel et al., 2004). In addition, Kliegel et al. (2007) have recently shown that improving older adults' intention formation may even lead to comparable prospective memory performance of young and old adults. Thus, the assumption that difficulties of old adults in the realization of delayed intentions might at least in part be due to a reduced strategic encoding capability suggests age-related differences in the neural correlates of intention formation. This prediction has been partly confirmed in the only available neurophysiological study investigating intention formation in young and old adults (West et al., 2003). West et al. found significant age-related differences in late fronto-polar and fronto-temporal slow waves. This suggests differences in the neural systems recruited to process intention encoding and differences in the time course between the two groups. Importantly, no study has so far confirmed their results and up to now there is no study available (neither behavioural nor neurophysiological) that has extended this question to a lifespan perspective.

The second line of reasoning to motivate a lifespan study on the neural correlates of intention encoding in prospective memory rests on the much broader *retrospective memory literature* on age differences in memory encoding. Numerous behavioural findings suggest that memory impairments in old adults might, to some extent, derive from difficulties in encoding the material to be remembered (e.g. Craik & Byrd, 1982; Light, 1991). It was suggested by Craik (1983) that these encoding deficits of old adults may derive from a reduced likelihood to spontaneously engage effective encoding strategies. This is in line with the less elaborate planning capabilities in prospective memory and suggests reduced

strategic encoding capabilities in old adults also for the encoding of prospective intentions. However, regarding developmental effects of encoding across childhood the findings are scarce despite a sound rationale for expecting an influence (Bauer, 2008) - explicit memory functions still develop beyond middle childhood (Kail, 2002; Murphy, McKone, & Slee, 2003) and differences in encoding are implied by older children reaching a learning criterion in encoding faster than younger children (for a review see Howe & O'Sullivan, 1997). From a neurophysiological perspective it was suggested that various regions supporting encoding of retrospective memory items (mainly PFC and MTL) undergo substantial age-related changes across the lifespan from childhood onwards (for a review see Werkle-Bergner et al., 2006). These changes were found in studies on neuromodulation (for a review see Bäckman & Farde, 2005; Benes, Taylor, & Cunningham, 2000), neuroanatomy (Giedd et al., 1999; Raz et al., 2005; for a review see Simons & Spiers, 2003; Sowell et al., 2003), and neuronal activity (Cabeza, 2002; for a review see Johnson, 2001; Thatcher, 1992). Accordingly, both EEG and neuroimaging studies (mainly with fMRI) have found age-related differences in neural correlates of successful memory encoding. One of the first event-related fMRI studies on this topic was conducted by Morcom, Good, Frackowiak, and Rugg (2003). Their findings pointed to age-related differences in the MTL and PFC when looking at successful encoding of young and old adults: While young adults showed higher activation in the left anterior temporal cortex when responding correctly, old adults displayed higher activation in bilateral regions of the anterior PFC (BA 10) and in the left supramarginal gyrus. Importantly, data suggest that the recruited network is the same for both age groups (e.g. Gutchess et al., 2005; Kirchhoff, Wagner, Maril, & Stern, 2000; Otten, Henson, & Rugg, 2001; Wagner, Koutstaal, & Schacter, 1999). What differs is the activation level of different parts of the network in the two age groups. Gutchess et al. (2005) reported comparable findings with pictorial material (Morcom used verbal material) and Grady, McIntosh and Craik (2003) identified age-related differences in the connectivity of prefrontal and medio-temporal regions using PET.

Although the event-related analysis of EEG data has a longer tradition, only few studies have looked at changes in the EEG signal resulting from successful encoding from a developmental perspective (for a review of the available ERP data up to 2000 see Friedman & Johnson, 2000) and most of them have focused on age differences across the adult lifespan (for an exception see Friedman, 1992). Surprisingly, a reliable difference between successful encoding (later remembered) and unsuccessful encoding (later

forgotten – with the former showing a higher activity) was only found for young adults (Friedman, Ritter, & Snodgrass, 1996). A possible explanation was given in the study by Friedman and Trott (2000) based on the assumption that older adults may fail to spontaneously engage in elaborative encoding strategies as the encoding task was incidental. The only lifespan ERP-study on successful encoding used a continuous recognition paradigm (Friedman, 1992). The findings indicate that encoding difficulties might explain the reduced retrospective memory performance during childhood and in old age. They also suggest that these two age groups might differ qualitatively in the strategies used to encode items for subsequent retrieval.

Taken together, behavioural and initial neurophysiological findings from both prospective and retrospective memory research suggest age differences in the neural correlates of intention encoding. Therefore, the aim of our study was to investigate age differences across the lifespan in neural correlates associated with encoding processes during the intention formation phase of a prospective memory task. The method used in the present study was an event-related EEG design allowing the distinction between neural correlates of remembered versus not-remembered intentions and the examination of the sequence of associated brain dynamics. The main analytical focus was on the source localization of identified and relevant ERPs using sLORETA. In accord with previous research (West et al., 2003a; West & Ross-Munroe, 2002), four modulations of the ERPs were targeted that have been shown to differentiate ongoing activity trials from intention formation trials: N2, late positivity complex (LPC), frontal slow wave (FPSW), and temporo-parietal slow wave (TPSW). Consequently, these modulations were then taken as time windows for the source localization with sLORETA. The N2 reflects a phasic negativity over occipito-parietal regions with a peak around 300 ms and differentiated between later realized and unrealized intention trials from ongoing activity trials. The N2 is in its duration clearly extended for old adults. Therefore, the N2 was divided in an early (250-350 ms) and a late portion (350-450 ms). The LPC reflects a positivity over the parietal region of the scalp and a negativity over the lateral frontal regions with a peak around 600 ms. As described by West et al. (2003a), the LPC probably reflects the P3 that is typically elicited by the presentation of a low-probability attention-demanding stimulus (Donchin & Coles, 1988) and reverses polarity over the lateral frontal regions when an average reference is used (Spencer et al., 2001). Like the N2 the LPC differentiated later realized and unrealized intention trials from ongoing activity trials in young and old adults (West et al., 2003a; West & Ross-Munroe, 2002). The FPSW reflects a sustained

negativity over the frontal-polar region of the scalp and lasts approximately from 500-1000 ms. For young adults, it showed greater negativity for later realized intention trials than for later unrealized intention trials and may therefore reflect a neural correlate of the effectiveness of intention encoding (West & Ross-Munroe, 2002). The TPSW was only identified in one study (West et al., 2003a) and it reflected a greater positivity for later realized intention trials than for later unrealized intention trials only in old adults. The TPSW is detected over temporo-parietal regions and lasts approximately from 800-1200 ms.

From an electrophysiological perspective, we expected differential age effects between adolescents and old adults compared to young adults. Based on previous research, these differences might primarily be found in later and longer lasting slow waves (FPSW, TPSW). From a functional perspective, we expected that successful encoding in adolescents may be supported to a larger degree by activity in the MTL and sensory structures than it is in older adults. This assumption is based on data showing that the PFC matures relatively late across adolescence and may therefore not be able to substantially contribute to successful encoding in children (Giedd et al., 1999; Pfefferbaum et al., 1994). Hence, other relevant brain regions in the encoding process – such as MTL and sensory regions which mature at a considerably faster rate (e.g. Giedd et al., 1999; Sowell et al., 2003) – need to take over. Predictions for old adults regarding neural correlates of successful intention encoding are more difficult to make because of possible individual adaptations to changes in encoding-relevant processes as well as increasing individual strategic and declarative knowledge which leads to high inter-individual variability (Werkle-Bergner et al., 2006). Consequently, older adults may be more likely to integrate new information into an existing body of knowledge by retrieving either semantic or episodic memory content. Given that retrieval processes during encoding are supposed to involve prefrontal areas (Fletcher & Henson, 2001; for a review see Simons & Spiers, 2003) this would predict that PFC activity is more strongly related to successful encoding in old adults than in adolescents.

3.2.2 Method

Participants

Fourteen adolescents (*M* = 12.8, *SD* = 0.6 years; 7 female), 14 younger adults (*M* = 22.5, *SD* = 1.4 years; 7 female), and 14 older adults (*M* = 70.1, *SD* = 5.5 years; 7 female) participated in the study[1]. Data of one older adult was excluded from the analyses due to a high level of artefact in the EEG. All participants were right-handed according to their score on the Edinburgh-Handedness-Test (Oldfield, 1971). They were in good health and none reported brain injuries, psycho-affective medication, drug consumption, or other diseases affecting brain functioning. All participants were native German speakers. A standard psychometric testing battery was performed to exclude participants scoring one standard deviation or more below age appropriate norms on verbal intelligence, psychomotor speed, and memory span. The young adults were students at the University of Zurich, the adolescents were recruited through newspaper advertisement, and the older adults were recruited at a lecture for senior citizens at the University of Zurich. All adolescents were high-school students in top level Swiss 6th school grade. All participants were paid 50 CHF for their participation and were provided with written and oral descriptions of the study before written informed consent was obtained. The experiments were conducted in agreement with the declaration of Helsinki.

Materials and Procedure

The prospective memory task followed West et al. (2003a) and consisted of 1200 trials equally divided into six blocks. The presentation time for each trial was fixed to four seconds, independent of response times and accuracy of the response. The inter-stimulus interval was set to zero ms (i.e., there was no pause or blank screen between trials). Each block included 172 ongoing activity trials and eight prospective memory sequences consisting of an intention formation trial, a prospective inhibit trial, and a prospective execute trial (see below). There were either 6 or 12 ongoing activity trials between the intention formation trials, the prospective inhibit trials, and the prospective execute trials. The number of ongoing activity trials between the prospective memory trials was randomized across blocks and fixed across participants. There were breaks after each experimental block lasting from three to five minutes.

Ongoing task. The ongoing task consisted of a semantic relatedness judgement task. In an ongoing activity trial, two words, one above the other, were presented in lowercase letters centred on the vertical and horizontal axis of a computer monitor. The word pairs were presented in six different colours (red, green, yellow, blue, grey and magenta). The participants' task was to decide whether the two words belonged to the same (e.g., cat and dog) or a different (e.g., table and car) semantic category. They were asked to press the 'n'-key with the right index finger if the words were related and the 'm'-key with the right middle finger if the words were unrelated. Participants were told that we were interested in their verbal ability and that they should rate word pairs according to their knowledge or their intuition when uncertain.

The words were taken from the category norms for the German language (Mannhaupt, 1983; Scheithe & Bäuml, 1995) and included nouns and verbs. The word pairs were generated following the procedure of West et al. (2003a). Accordingly, words from 50 categories excluding names of persons, cities, states, colleges, universities, and members of clergy were combined to have the same number of vowels and approximately the same number of consonants. Each word appeared twice over the course of the task (i.e., once in a related and once in an unrelated pair). The related word pairs were from the same category, whereas the unrelated word pairs were formed by randomly re-pairing words across categories.

Prospective memory task. On *intention formation trials* in lieu of a word pair, one of two possible letter strings ('cccc' or 'vvvv') were presented either in grey or magenta. The participants were instructed to press the corresponding button on the keyboard ('c'-key with the left middle finger and the 'v'-key with the left index finger) and to remember the colour of the letter and the letter itself. Hence, they were to form the intention to press the target key when a word pair was presented in the target colour. Extending West et al.'s (2003a) procedure we included prospective inhibit trials. *Prospective inhibit trials* represented the first occurrence of a word pair in the target colour after the intention formation trial. For these trials, participants were to notice the prospective cue, but were required to make a semantic judgment and, therefore, to postpone the prospective response. The prospective inhibit trials allowed us to examine the frequency of false alarms for these trials that provided an index of the efficiency of the retrospective component of prospective memory. *Prospective execute trials* represented the second time a word pair appeared in the prospective colour. For these trials the participants were to make the prospective response.

One prospective memory sequence therefore consisted of encoding and retaining one of two possible prospective cues (e.g., the colour magenta) as well as one of two possible prospective actions (e.g., press the key "v"; for an illustration see Figure 1.). This constituted the intention formation phase. When, after several ongoing activity trials, a word-pair appeared in the previously encoded target colour (e.g., magenta), the participant was supposed to notice this event, but to postpone the prospective response. After, several more ongoing activity trials a second word-pair appeared in the target colour reflecting the prospective execute trial (e.g., magenta) the prospective response had to be initiated and executed (pressing the key "v").

Before the experimental blocks, participants performed two practice blocks, each repeatable until the task was fully understood. The first block followed the instructions for the semantic categorization task and included 63 ongoing activity trials. The second block started after the prospective memory instructions were explained and consisted of 54 ongoing activity trials, and three prospective memory sequences. Participants were encouraged to ask questions during and after the practice blocks to ensure that they understood the instructions before the experimental blocks began.

Recording and analysis of electrophysiological data

Recording. The electroencephalogram (EEG) was continually recorded while participants performed the task. The EEG was amplified with a BrainAmpMR (Brain Products GmbH), digitized at 500 Hz, and recorded with a 16 bit A/D converter. During recording, a low pass filter (100 Hz) was applied. Both the notch filter and high pass filter were off (BrainVision Recorder Software). The EEG was recorded from an array of 32 Ag/AgCl scalp electrodes which were placed according to the 10-20 system being sewn into an EasyCap or affixed to the skin with an adhesive patch. During recording inter-electrode impedances were maintained below 10 kΩ and all electrodes were referenced to electrode FCz. Vertical and horizontal eye movements were recorded with electrodes placed below the right and left eyes.

Processing. For data analysis, all electrodes were re-referenced to an average reference as suggested in the guidelines published by the Society for Psychophysiological Research (Picton et al., 2000). The recorded EEG was bandpass-filtered (0.1-30 Hz, time constant 1.59155s, 48 dB/oct). ERP analysis epochs were extracted off-line and included a 200 ms of pre-stimulus baseline and 1200 ms of post-stimulus activity. Ocular artefacts associated with blinks, as well as additional eye movements and articulated muscular

artefacts were corrected using independent component analysis (ICA) software (http://www.puk.unibe.ch/tk2/tk.htm). This is a publicly available freeware for the VisionAnalyzer software (Brainproducts GmbH) which separates the mixture of independent EEG signals into 30 factors (corresponding to the number of electrodes used) by conducting a component analysis. Jung et al. (1998) demonstrate that the unwanted artefacts will be contained in one or more components that can be removed and the artefact free EEG reconstructed from the remaining components. To identify the ocular components we compared the timing and topographical distribution of the artefacts in the EEG against that of the independent components. Following ocular correction, trials contaminated by remaining artefacts were rejected with the Raw Data Inspector (Vision Analyzer software, Brainproducts GmbH).

ERPs were averaged for the following artefact free trials: (1) *Ongoing activity trials,* trials immediately preceding intention formation trials (adolescents: M = 45.79, SD = 2.36, range = 41-48; young adults: M = 47.00, SD = 1.18, range = 45-48; old adults: M = 43.85, SD = 3.05, range = 37-48), (2) *later realized intention trials,* intention formation trials which later elicited a correct prospective response (adolescents: M = 38.79, SD = 3.83, range = 33-45; young adults: M = 41.71, SD = 4.30, range = 33-46; old adults: M = 30.69, SD = 8.04, range = 13-41), (3) *later unrealized intention trials*, intention formation trials which later elicited a false response to prospective cues (i.e., wrong letter, ongoing response, miss; adolescents: M = 6.71, SD = 3.15, range = 1-11; young adults: M = 4.14, SD = 3.39, range = 1-11; old adults: M = 11.69, SD = 6.28, range = 3-27). The number of artefact free trials corresponds approximately to the ones calculated with in the two previous studies investigating intention formation in prospective memory (West et al., 2003a; West & Ross-Munroe, 2002).

Analysis of mean amplitude. All statistical tests were performed on mean voltages averaged over selected electrodes and temporal windows in which modulations of interest were observed in previous research (West et al., 2003a; West & Ross-Munroe, 2002) relative to mean voltage of the 200 ms pre-stimulus baseline activity. The following five event-related potentials (ERPs) were considered for analyses of differences in mean amplitude between groups and conditions: (1) *N2early:* early portion of N2 between 250-350 ms after stimulus onset, recorded at electrodes P7, P8, O1, O2; (2) *N2late:* late portion of N2 between 350-450 ms after stimulus onset, recorded at electrodes P7, P8, O1, O2; (3) *LPC:* late positivity complex between 500-700 ms after stimulus onset, recorded at electrodes CP3, CP4, P3, P4, F7, F8, FT7, FT8; (4) *FSW:* frontal slow wave between 500-

1000 after stimulus onset, recorded at electrodes Fp1, Fp2; (5) *TPSW*: temporo-parietal slow wave between 800-1200 ms after stimulus onset, recorded at electrodes P7, P8, TP7, TP8.

sLORETA analysis. Standardized low-resolution electromagnetic tomography (sLORETA) was performed on the basis of the scalp-electrode electric potential distribution (Pascual-Marqui, 1999, 2002; Pascual-Marqui et al., 1994) to localize differential neural recruitment between groups and conditions. sLORETA was used to estimate the three-dimensional intra-cerebral current density distribution in 6239 voxels with a spatial resolution of 5 mm and a voxel volume of 0.125 cm^3. The evaluated ERPs were subjected to a sLORETA analysis. The obtained images were compared on a voxel-wise basis for inter-group differences between adolescents and younger adults and between older adults and younger adults in ongoing activity trials, correct intention formation trials, and incorrect intention formation trials.

Five time frames of interest were defined based on the temporal windows of the analysed ERPs. The statistical comparisons were conducted using *t*-tests for independent samples corrected for multiple comparisons (Nichols & Holmes, 2002). These patterns of descriptive *p*-values were plotted in statistical probability maps (SPM). sLORETA values were transformed logarithmically to achieve normal distribution and were normalized on a subject-wise basis. This latter transformation multiplies for each individual every single voxel's activity by the inverse of the total sLORETA activity over all voxels and all time frames for this subject and serves to avoid a potential confound between the direct between-group comparison and the general group differences (i.e., the results from comparing adolescents with younger adults with the fact that adolescents as a group display larger amplitudes).

3.2.3 Results

Results focus on age-related differences in neural recruitment for the ongoing activity, later realized and later unrealized intention formation. Effect size is reported as eta-squared (η^2). Statistical tests were performed using the multivariate *F*-ratio (repeated-measures MANOVA). Post hoc Tukey tests qualified the results in case of a significant main effect of age. The Greenhouse–Geisser correction was conducted if sphericity could not be assumed and epsilon (ε) is reported as a value of correction. Pairwise comparisons of the main effect of condition are adjusted for multiple comparisons using the Bonferroni-correction.

Performance accuracy. The behavioural data on prospective memory execution (reported in Zöllig et al., 2007) demonstrated an inverted U-shaped function with adolescents and old adults performing less accurate on the prospective memory task compared to young adults. Behavioural as well as neurophysiological findings on this phase also suggested differential age differences in the processes contributing to prospective memory execution across the lifespan.

Electrophysiological data

ERPs.

Neural activity associated with the formation of an intention was examined by comparing the ERPs elicited on intention formation trials that were later associated with a realized intention (later realized intention trials), intention formation trials that were later associated with an unrealized intention (later unrealized intention trials), and ongoing activity trials immediately preceding intention formation trials. Five modulations of ERPs were observed that differentiated ongoing activity trials from intention formation trials (i.e., N2 early, N2 late, LPC, FPSW, TPSW). Figure 9 presents the different grand averaged ERPs for the three trials at selected electrode locations and Table 4 summarizes the mean voltage. The topography of these modulations are portrayed in Figure 10.

N2. As described in previous research (West et al., 2003a; West & Ross-Munroe, 2002), a prolonged negativity for older adults over occipital-parietal regions that was temporally more extended than in young adults was observed. In this late N2, adolescents reversed polarity and showed a positive modulation. Accordingly, the two time windows of an early and late portion of the N2 were analysed separately (N2e = early N2, N2l = late N2). Both epochs of the N2 were quantified in a 3(age) x 3(condition) x 2(hemisphere) x 2(electrodes: P7-P8, O1-O2)-MANOVA.

N2e (250-350 ms epoch). This ERP modulation showed a significant main effect of condition ($F(1.4,54.8) = 22.04$ ($\varepsilon = .72$), $p < .001$, $\eta^2 = .37$) differentiating ongoing activity trials from later realized ($p < .001$) and later unrealized intention trails ($p < .01$) with the latter two not differing significantly showing a greater negativity. However, the condition x group interaction did not reach significance ($F < 1.00$, $\eta^2 = .02$) suggesting that the early portion of the N2 in the different conditions was similar for the three groups. There was a significant interaction of age x hemisphere ($F(2,38) = 6.19$, $p < .01$, $\eta^2 = .25$) with adolescents showing a larger amplitude over the right compared to the left hemisphere, whereas both young and old adults showed the reverse picture.

Table 4. Mean voltage (in mV) for adolescents, young adults, and old adults in the ERPs.

			Ongoing	Int realized	Int unrealized
N2e	Adolescents	*M (SD)*	.214 (2.30)	-2.04 (3.18)	-1.18 (5.12)
	Young adults	*M (SD)*	-1.88 (2.06)	-4.90 (3.78)	-4.11 (5.18)
	Old adults	*M (SD)*	-2.05 (1.75)	-4.89 (2.52)	-4.48 (2.53)
N2l	Adolescents	*M (SD)*	3.12 (2.88)	6.63 (3.60)	7.13 (7.22)
	Young adults	*M (SD)*	-.15 (1.54)	-1.02 (2.71)	-.50 (3.70)
	Old adults	*M (SD)*	-.75 (1.76)	-3.62 (2.41)	-3.02 (2.36)
LPC p	Adolescents	*M (SD)*	1.44 (2.04)	11.04 (2.84)	12.38 (3.33)
	Young adults	*M (SD)*	1.16 (1.15)	4.79 (1.52)	5.34 (2.83)
	Old adults	*M (SD)*	.70 (1.24)	2.98 (1.92)	2.40 (1.68)
LPC f	Adolescents	*M (SD)*	-.83 (1.90)	-9.08 (2.79)	-11.66 (3.84)
	Young adults	*M (SD)*	.06 (1.31)	-3.10 (1.65)	-3.91 (2.76)
	Old adults	*M (SD)*	.08 (1.28)	-1.41 (1.44)	-.94 (1.61)
FPSW	Adolescents	*M (SD)*	-1.78 (2.21)	-8.95 (2.53)	-8.40 (3.08)
	Young adults	*M (SD)*	-1.03 (1.73)	-3.44 (1.91)	-4.22 (3.46)
	Old adults	*M (SD)*	-.29 (1.52)	-1.42 (2.28)	-.74 (1.97)
TPSW	Adolescents	*M (SD)*	.66 (1.39)	-1.96 (2.25)	-2.32 (4.22)
	Young adults	*M (SD)*	-.40 (.84)	.48 (1.31)	-.16 (2.27)
	Old adults	*M (SD)*	-.09 (.81)	.41 (1.69)	.20 (1.88)

Int = intention

N2l (350-450 ms epoch). This ERP modulation revealed a significant condition x age interaction ($F(2.8,53.1) = 8.84$ ($\varepsilon = .70$), $p < .001$, $\eta^2 = .32$). In a follow-up of this interaction, separate analyses of the main effect of condition for each group were performed. In adolescents, the main effect of condition was significant ($F(1.3,17.2) = 6.09$ ($\varepsilon = .66$), $p < .05$, $\eta^2 = .32$) differentiating ongoing activity trials from later realized intention trials ($p < .01$); later unrealized intention trials differed from neither of the two (a trend for ongoing activity trials, $p > .07$). In old adults, this effect was also significant ($F(1.9,22.3) = 19.72$, $p < .001$, $\eta^2 = .62$) differentiating ongoing activity trials from later realized ($p < .01$) and later unrealized intention formation trials ($p < .001$). In young adults, the main effect of condition was not significant ($F < 1.0$, $\eta^2 = .06$). These findings indicate that the occipital-parietal negativity was significant between 350 and 450 ms in adolescents and older adults, but not in younger adults. The only other relevant effect to be significant

was the main effect of age ($F(2,38) = 27.34$, $p < .001$, $\eta^2 = .59$) with post-hoc tests (Tukey) revealing that adolescents elicited a significantly higher (and positive) amplitude compared to both young adults ($p < .001$) and old adults ($p < .001$), with the latter two not differing significantly ($p > .22$) and displaying a negative amplitude.

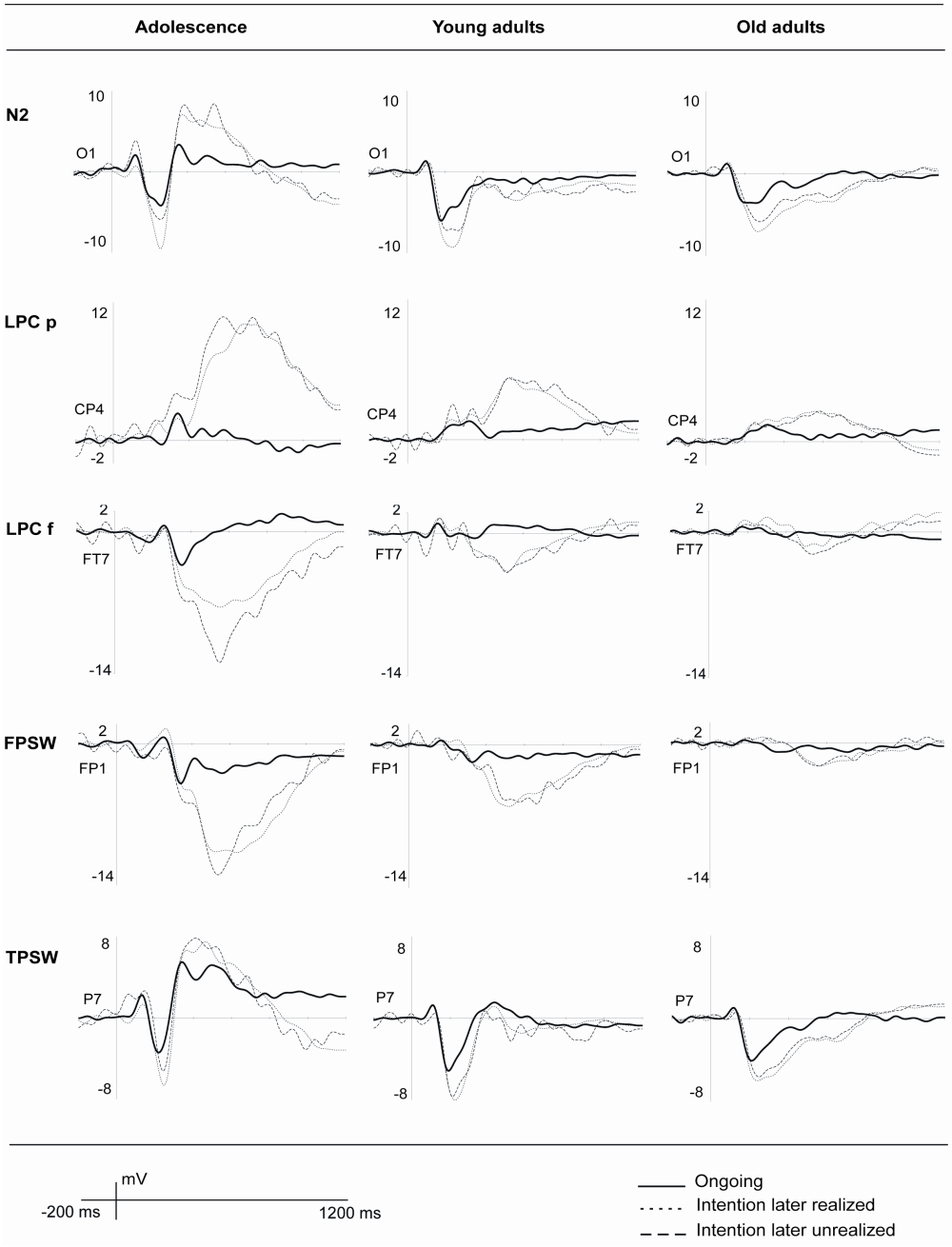


Figure 9. Grand-averaged event-related brain potentials at selected electrodes demonstrating the N2 (early and late), the LPC (parietal and frontal), the FPSW, and the TPSW for ongoing activity, later realized and later unrealized intention formation trials in all three age groups. (Note: the data are displayed with a 10 Hz high cut-off filter)

LPC. According to previous findings (West et al., 2003a), the LPC reverses polarity from the parietal region to the lateral fronto-temporal region regions of the scalp. West et al. suggested that the LPC might reflect the P3 that is typically observed when a low-probability stimulus which demands attention is presented (Donchin & Coles, 1988). This effect reverses polarity over the lateral frontal regions when an average reference is used (Spencer et al., 2001). The LPC was quantified in a 3(age) x 3(condition) x 2(hemisphere) x 4(electrodes: CP3-CP4, P3-P4, F7-F8, FT7-FT9)-MANOVA. Consistent with the reversing of polarity, the interaction of condition x electrode was significant (F(1.9,74.6) = 129.17 (ε = .33), p < .001, η^2 = .77). Also significant was the age x condition x electrode interaction (F(3.9,74.6) = 33.33 (ε = .33), p < .001, η^2 = .64). This interaction was followed up by age x condition analyses for parietal (CP3-CP4, P3-P4) and lateral frontal regions (F7-F8, FT7-FT8) separately.

The ERP modulation for the *parietal electrodes* revealed a significant main effect of condition (F(1.5,59.1) = 168.93 (ε = .78), p < .001, η^2 = .82) differentiating ongoing activity trials from later realized and later unrealized intention trials (p < .05), the latter two not differing significantly. There was a significant condition x age interaction (F(1.5,59.1) = 37.65 (ε = .78), p < .001, η^2 = .66) with adolescents and young adults showing the highest amplitude for later unrealized intention trials, whereas old adults showed the highest amplitude in later realized intention trials. The smallest amplitude was for all age groups in ongoing trials. In a follow-up of this interaction, separate analyses of the main effect of condition for each group were performed. In neither of the groups did the difference between later realized and later unrealized intention formation trials reach significance (p > .05), but there was a trend in old adults (p > .06). The main effect of age was significant (F(2,38) = 43.63, p < .001, η^2 = .70) with adolescents displaying the highest amplitude compared to both young and old adults (p < .001) followed by young adults and with the smallest amplitude in old adults (significant also compared to young adults, p < .05).

The ERP modulation for the *frontal electrodes* revealed a significant main effect of condition (F(1.5,58.7) = 102.21 (ε = .77), p < .001, η^2 = .73) differentiating ongoing activity trials from both intention formation trials (p < .001) and also later realized from later unrealized intention trials (p < .05). The condition x age interaction was significant (F(1.5,58.7) = 28.84 (ε = .77), p < .001, η^2 = .60) and a separate analyses of the main effect of condition for every age group revealed that the difference between later realized and later unrealized intention trials is only significant in adolescents (p < .05). This is in line

with previous research which has not found this difference in young and old adults (West et al., 2003a). Hence, for adolescents, but not for young and old adults the LPC on frontal electrodes might reflect a neural correlate of the effectiveness of the intention encoding.

Again, the main effect of age was significant ($F(2,38) = 52.80$, $p < .001$, $\eta^2 = .74$) showing the same pattern as at parietal electrodes with adolescents showing a higher amplitude compared to young adults and old adults ($p < .001$). However, young adults and old adults did not differ significantly ($p > .06$). The latter is consistent with previous findings from West et al. (2003a) describing age-related differences over parietal regions but not over fronto-temporal regions.

FPSW. The FPSW was quantified in a 3(age x 3(condition) x 2(hemisphere) MANOVA including Fp1 and Fp2. This ERP modulation showed a significant main effect of condition ($F(2,76) = 58.60$, $p < .001$, $\eta^2 = .61$) differentiating ongoing activity trials

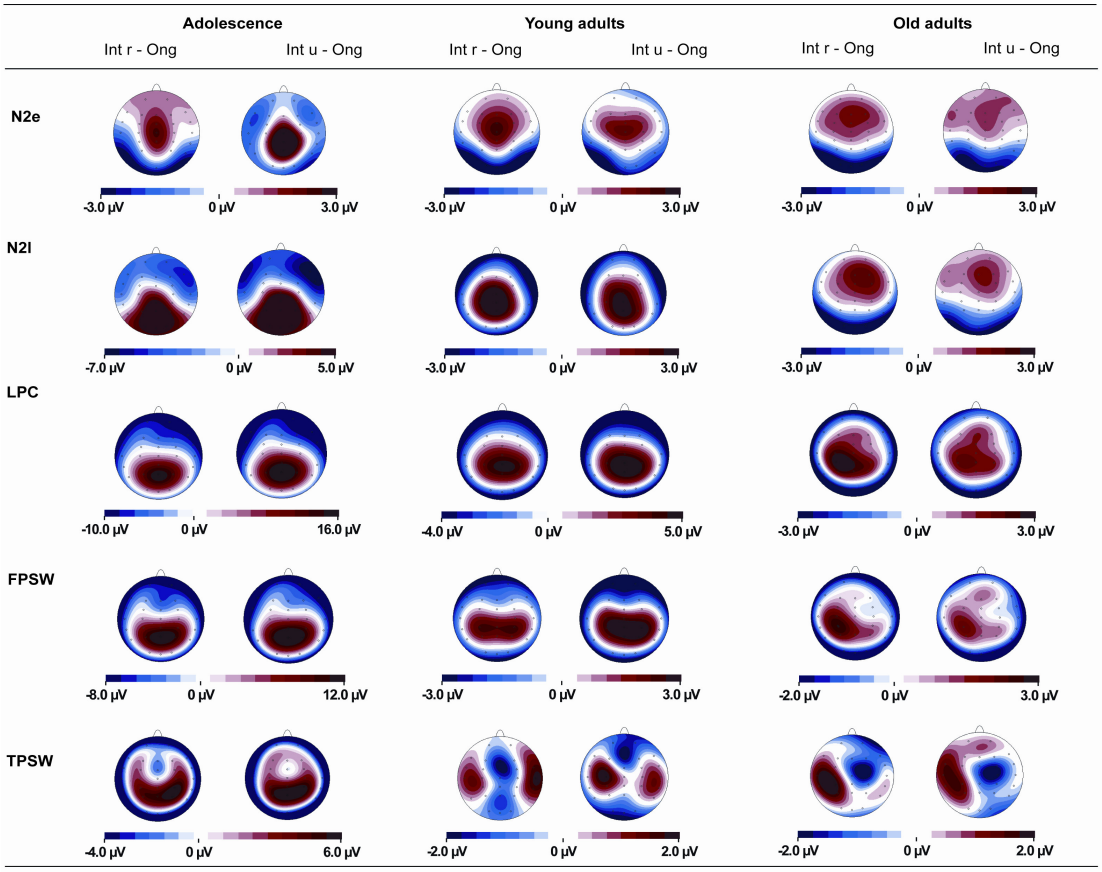


Figure 10. Topographical maps of adolescents, young adults, and old adults representing differences between later realized intention formation trials (Int r) and ongoing activity trails (Ong) and between later unrealized intention formation trials (Int u) and ongoing activity trails (Ong) during the time windows that were used for analyses of the ERPs. Note the different scaling to illustrate the topographical distribution.

from later realized and later unrealized intention trials ($p < .001$), the latter two not differing significantly. The condition x age interaction was significant ($F(4,76) = 16.21$, $p < .001$, $\eta^2 = .46$) and a separate analyses of the main effect of condition for every age group revealed that this condition effect is significant in adolescents ($p < .001$) and young adults ($p < .001$) and not present in old adults ($p > .1$). This is consistent with previous research (West et al., 2003a) finding no main effect of condition in old adults. The main effect of age was significant ($F(2,38) = 28.27$, $p < .001$, $\eta^2 = .60$) with post-hoc tests (Tukey) revealing that adolescents had a higher amplitude than young adults ($p < .001$) which have again a higher amplitude than old adults ($p < .05$).

TPSW. The TPSW was quantified in a 3(age) x 3(condition) x 2(hemisphere) x 2(electrodes: P7-P8, TP7-TP8) MANOVA. This ERP modulation revealed a significant condition x age interaction ($F(4,76) = 5.16$, $p < .01$, $\eta^2 = .21$). The follow-up of this interaction in separate analyses for each group revealed that only adolescents showed a significant difference between conditions ($F(2.26) = 6.25$, $p < .01$, $\eta^2 = 0.32$) with a significantly smaller amplitude in ongoing trials compared to both later realized and later unrealized intention trials ($p < .05$), latter two not differing significantly. These findings indicate that the fronto-temporal slow wave was significant in adolescents, but not in old and young adults. This is only partially in line with previous research having reported no main effect of condition for young but a significant effect for old adults (West et al., 2003a). Main effect of age was significant ($F(2,38) = 3.37$, $p < .05$, $\eta^2 = .15$), but the multiple comparisons with post-hoc tests (Tukey) did not reveal any significant difference between the groups, only a trend of adolescents to show a larger amplitude compared to old adults ($p > .056$), the other comparisons were not significant.

sLORETA.

Source localization was performed to investigate age-related differences in neural recruitment associated with later realized and later unrealized intention formation. The source localization for younger adults provided a baseline for the paired comparisons, as in this group the underlying neural generators are assumed to be fully developed.

The statistical probability maps from the sLORETA analyses are displayed in Figure 11 where local maxima of inter-group differences in the three-dimensional current density distribution for ongoing activity, later realized and later unrealized intention formation trials are shown for the time windows of the five ERP components. Table 5 summarizes the brain regions that demonstrated differential activation across the groups and includes X, Y, Z-MNI coordinates and the *t*-value at the local maxima. Most interesting are the findings on differential age effects between later realized and later unrealized intention trials.

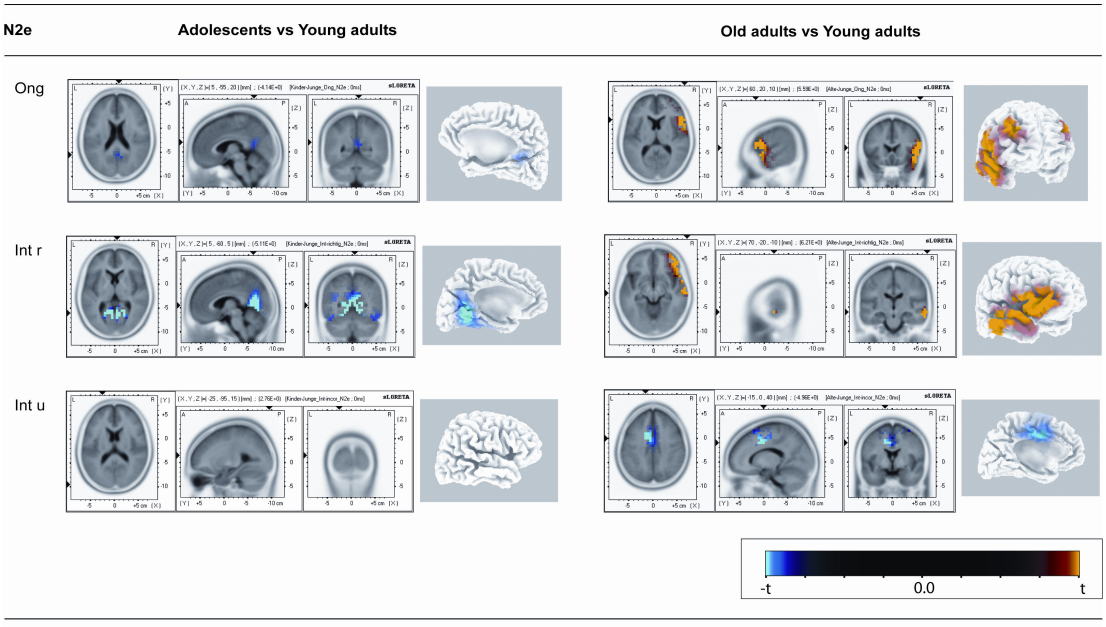
N2 time frame. For the earliest time window of the *N2e* and in later realized intention trials older adults displayed a higher activation in right temporal and (to a lesser extent) in frontal areas. Ongoing trials involved similar brain regions, but with the maximum in frontal regions. A different picture emerged for later unrealized intention trials with a reduced activity of old adults in middle central regions of the brain (middle cingulum). Adolescents did not differ from young adults in later unrealized intention trials, but had a reduced activation in inferior occipital-parietal regions compared to young adults in later realized intention trials.

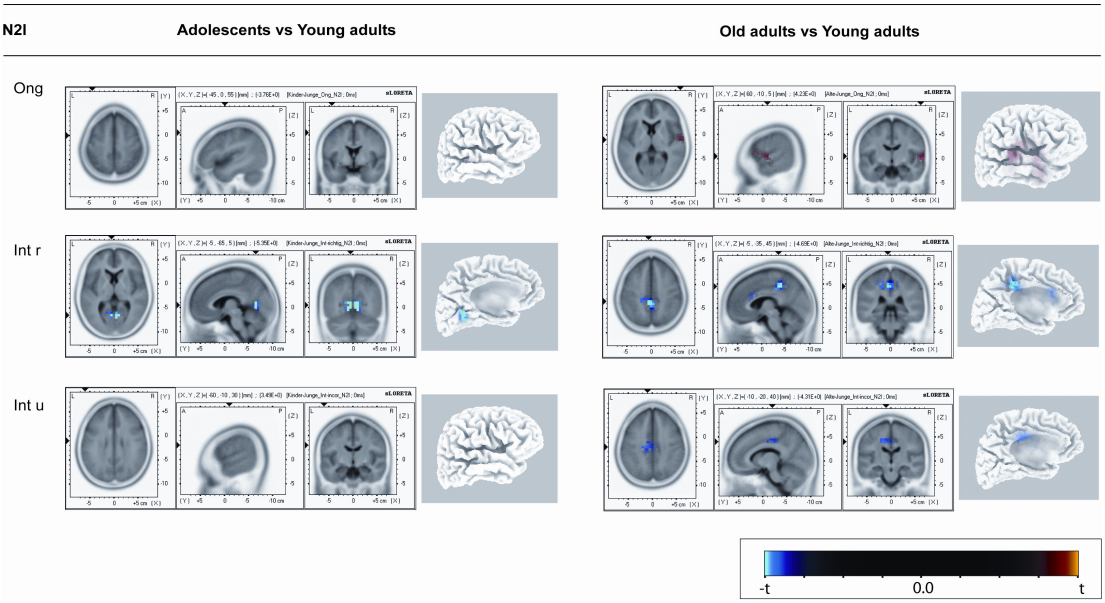
Although the later portion of the N2 (*N2l*) showed a prolonged negativity in old adults and a polarity-reversed pattern in adolescents (ERPs), there were hardly any differences between old adults and young adults nor between adolescents and young adults in all three conditions.

LPC time frame. In the time window of the LPC there were mainly differences between adolescents compared to young adults. Most interestingly, adolescents showed a higher activation of occipital regions (more pronounced in the right hemisphere) compared to young adults in later realized intention trials. This pattern was also present in later unrealized intention trials (more pronounced in the left hemisphere) but did not reach significance. This might suggest that if adolescents fail to recruit more occipital regions than young adults in intention formation trials during the time window of the LPC, they are not able to successfully encode the intention.

FPSW time frame. The same pattern was found during the time window of the FPSW with adolescents displaying a higher activation of mainly right occipital regions in later realized intention trials compared to young adults. Again for the later unrealized intention trials this activation was smaller and shifted to the left hemisphere. Older adults, on the other hand, recruited more resources in right prefrontal areas than young adults in order to later correctly realize the intention

TPSW time frame. These activations persisted more or less during the time window of the TPSW. However, the differences between adolescents and young adults became smaller and were only significant in later realized intention trials in right occipital regions. The activation differences between old and young adults in right prefrontal persisted and expanded furthermore to right middle and superior temporal regions. The persistently reduced activation in posterior regions of the cingulum of old adults during ongoing trials beginning at 500 ms suggests a reduced readiness and preparation for action (Cunnington et al., 2006). This is in line with findings suggesting an age-related decline in the recruitment of attentional processes that facilitate cue detection (Smith & Bayen, 2004, 2006; West & Bowry, 2005).




N2l
Adolescents vs Young adults
Old adults vs Young adults
Ong
Int r
Int u
-t
0.0
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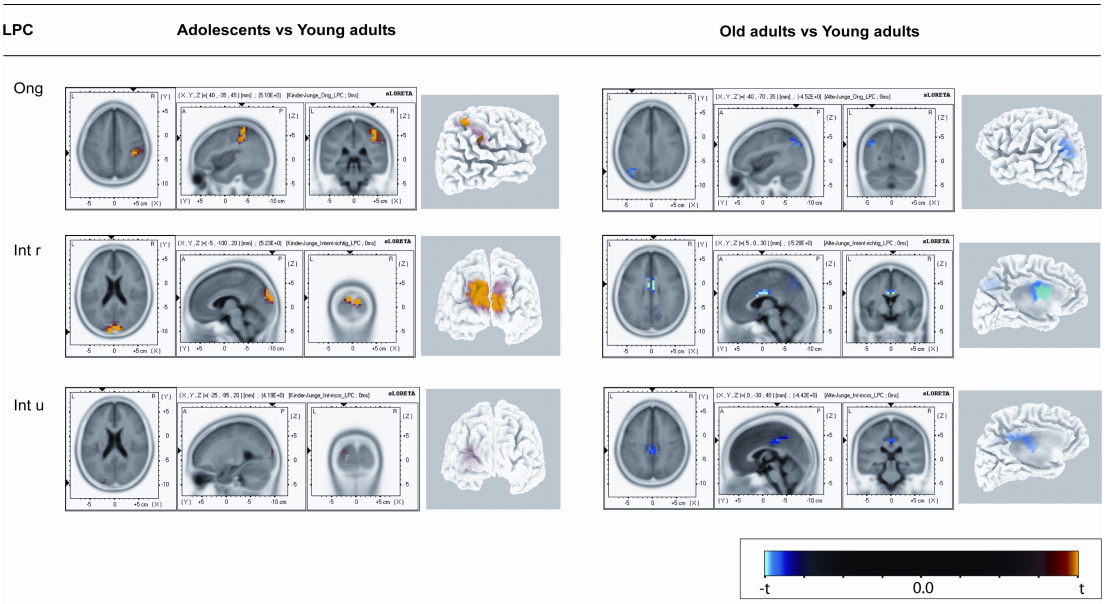
LPC
Adolescents vs Young adults
Old adults vs Young adults
Ong
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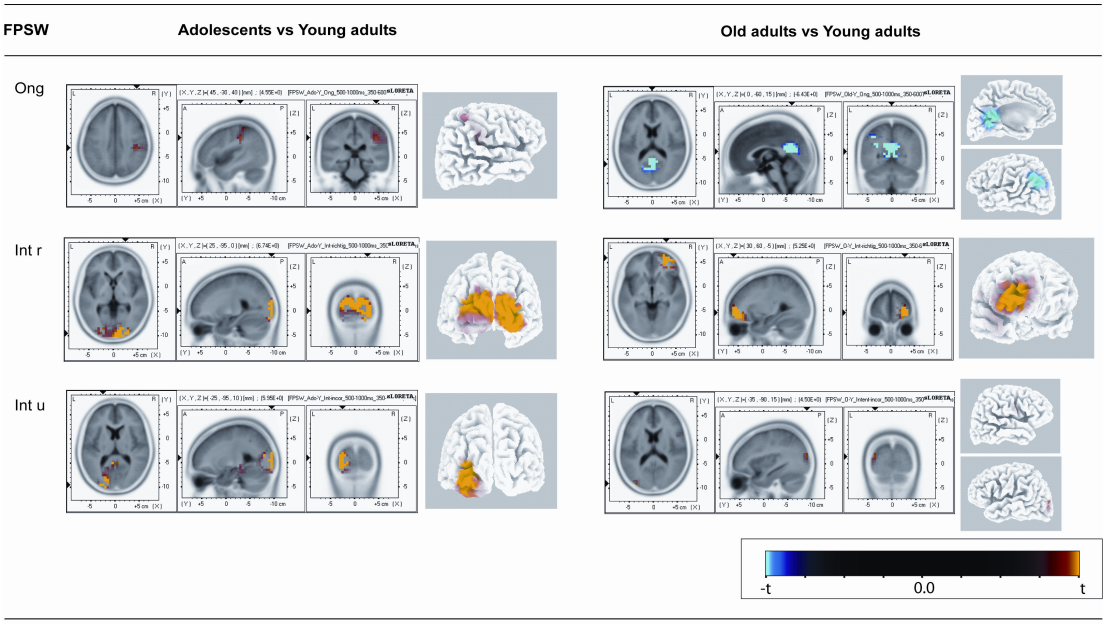

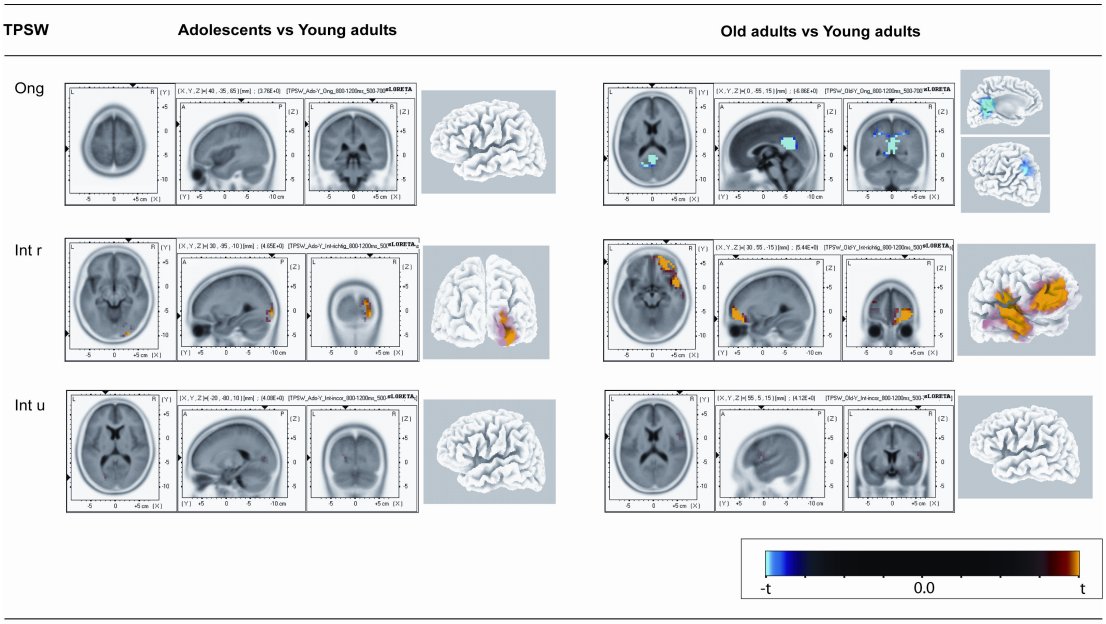

Figure 11. Statistical probability maps (SPM) of the source localization with sLORETA for differences between adolescents / young adults and old adults / young adults. Results are significant at the $p < .05$ level (blue colour = significantly lower current density, red colour = higher current density).

Table 5. Local maxima in current density differences between adolescents (Ado) and young adults (YAd), and between old adults (OAd) and young adults calculated with standardized low-resolution electromagnetic tomography (sLORETA).

Trial	Comparison	Brain region	HS	MNI coordinates			$t_{X, Y, Z}$
				X	Y	Z	
OA							
N2e	Ado vs. YAd	Posterior Cingulate (BA 31)	M	5	-55	20	-4.59*
	OAd vs. YAd	Inferior frontal gyrus (BA 44, 45, 47)	R	60	20	10	4.56*
		Middle frontal gyrus (BA 46)	B				
		Inferior, middle and superior temporal gyrus (BA 20, 21, 38)	R				
N2l	Ado vs. YAd	Middle frontal gyrus (BA 6, 8)	L	-45	0	55	-4.65
	OAd vs. YAd	Superior temporal gyrus (BA 22, 42)	R	60	-10	5	4.63*
LPC	Ado vs. YAd	Inferior parietal lobe (BA 40)	R	40	-35	45	4.73
	OAd vs. YAd	Precuneus (BA 39, 19)	L	-40	-70	35	-4.73
FPSW	Ado vs. YAd	Postcentral gyrus (BA 2), Inferior parietal lobe (BA 40)	R	45	-30	40	4.81*
	OAd vs. YAd	Posterior cingulate (BA 23, 30, 31)	M	0	-60	15	-4.72*
		Precuneus (BA 19), Superior parietal lobe (BA 7), Angular gyrus (BA 39)	L				
TPSW	Ado vs. YAd	Postcentral gyrus (BA 2, 40)	R	40	-35	65	4.77
	OAd vs. YAd	Posterior cingulate (BA 23, 30, 29, 31)	M	0	-55	15	-4.77*
		Superior parietal lobe (BA 7)	L				
Int r							
N2e	Ado vs. YAd	Posterior cingulate (BA 30, 29, 23)	M	5	-60	5	-4.62*
		Lingual gyrus (BA 18, 19)					
	OAd vs. YAd	Middle temporal gyrus (BA 21)	R	70	-20	-10	4.67*
		Inferior, superior temporal gyrus (BA 20, 22, 42, 41)					
		Inferior frontal gyrus (BA 45, 46)					
N2l	Ado vs. YAd	Cuneus (BA 30)	M	-5	-65	5	-4.64*
		Lingual gyurs (BA 18, 19)					
	OAd vs. YAd	Precuneus (BA 7)	M	-5	-35	45	-4.67*
		Cingulate gyrus (BA 31)					
LPC	Ado vs. YAd	Cuneus (BA 18, 19, 17)	M	-5	-100	20	4.68*

	OAd vs. YAd	Cingulate gyrus (BA 24, 32, 33)	M	5	0	30	-4.68*
FPSW	Ado vs. YAd	Middle occipital gyrus (BA 18, 19), Lingual gyrus (BA 17), Cuneus (BA 30)	R	25	-95	0	4.67*
	OAd vs. YAd	Superior frontal gyrus (BA 10, 11)	R	30	60	-5	4.74*
TPSW	Ado vs. YAd	Inferior occipital gyrus (BA 18, 17), fusiform gyrus (BA 19)	R	30	-95	-10	4.56*
	OAd vs. YAd	Superior and middle frontal gyrus (BA 11, 10)	R	30	55	-15	4.68*
		Superior and middle temporal gyrus (BA 38, 21)	R				
Int u							
N2e	Ado vs. YAd	Middle occipital gyrus (BA 18)	L	-25	-95	15	4.65
	OAd vs. YAd	Cingulate gyrus (BA 24, 32)	M	-15	0	40	-4.58*
N2l	Ado vs. YAd	Precentral gyrus (BA 4)	L	-60	-10	30	4.66*
	OAd vs. YAd	Cingulate gyrus (BA 24, 31)	M	-10	-20	40	-4.61*
LPC	Ado vs. YAd	Cuneus (BA 19)	L	-25	-95	20	4.72*
	OAd vs. YAd	Cingulate gyrus (BA 31, 24)	M	0	-30	40	-4.70*
FPSW	Ado vs. YAd	Middle occipital gyrus (BA 18, 19), Cuneus (BA 17)	L	-25	-95	10	4.71*
	OAd vs. YAd	Middle occipital gyrus (BA 19, 18) Inferior frontal gyrus (BA 45)	L	-35	-90	15	4.74*
TPSW	Ado vs. YAd	Cuneus (BA 17, 18)	L	-20	-80	10	4.69
	OAd vs. YAd	Inferior frontal gyrus (BA 44)	R	55	5	15	4.77

OA = ongoing activity, Int r = Intention realized, Int u = Intention unrealized; BA = Brodmann area. *p<.05.

3.2.4 Discussion

The aim of the present paper was to investigate age differences across the lifespan in neural correlates associated with the encoding of a delayed intention. The study focused on two research questions: (1) Are the age-related differences in prospective memory performance determined amongst others by differences in the intention formation phase and (2) if so, do adolescents' and old adults' neural responses not only differ compared to young adults but also compared to each other? The main analytical focus of this study was on the source localization of identified ERPs with sLORETA. Hence, the discussion first addresses age differences in the mean amplitude of the ERPs and then elaborates on age differences in activated brain regions during these time windows.

ERPs and the formation of an intention.

The *N2* in young adults reflected a phasic negativity over occipito-parietal regions of the scalp lasting from 250 to 350 ms, whereas old adults showed a temporally extended negativity lasting for several hundred milliseconds. In contrast, the N2 in adolescents reversed polarity after 350 ms and showed a pronounced positivity over occipito-parietal regions of the scalp. It seems, therefore, that adolescents and old adults reacted differently in the late part of the N2 both compared to young adults and compared to each other. As expected, the N2 did not differentiate between later realized and later unrealized intention trials. Therefore, it seems that the N2 does not reflect a neural correlate of the processes supporting successful encoding of an intention.

The *LPC* reflected a positivity over parietal regions of the scalp and a reversed polarity over lateral fronto-temporal regions lasting from 500 – 700 ms. Thus, young and old adults differed only over parietal but not over lateral frontal regions of the scalp. As expected, the LPC of young and old adults did not differentiate between later realized and later unrealized intention formation trials. However, in adolescents the LPC over lateral fronto-temporal regions did differentiate between these two trials suggesting, therefore, that in adolescents in may reflect a neural correlate of successful encoding.

The *FPSW* reflected a sustained negativity over the fronto-polar region beginning at 500 ms and lasting for several hundred milliseconds. The condition effect was only present for young adults and adolescents, which is in line with previous research (West et al., 2003a) finding a condition effect only for young but not for old adults. However, the

reported differentiation between later realized and later unrealized intention formation trials could not be confirmed.

The *TPSW* in young and old adults reflected a sustained positivity over the temporo-parietal region beginning at 800 ms and lasting for the remainder of the ERP. Neither young nor old adults displayed a significant effect of condition. Hence, the previously reported differentiation in old adults between later realized and later unrealized intention trials could not be replicated in our data. In adolescents, the TPSW reversed polarity and reflected a sustained negativity differentiating between ongoing and intention formation trials.

Overall, a differentiation between later realized and later unrealized intention formation trials – which would suggest a neural correlate of effective encoding – could not be detected in the expected late slow waves (FPSW and TPSW). However, such a differentiation was found for adolescents in the time window of the LPC over lateral fronto-temporal regions. Furthermore, this effect in adolescents seems to point in the opposite direction as studies from retrospective memory research suggest a higher activation or amplitude during encoding for later remembered versus later not remembered items (the so-called subsequent memory effect (Sm), for a review see Werkle-Bergner et al., 2006). This missing subsequent memory effect in our data might be due to several reasons: (1) It is possible that a difference between later realized and later unrealized intention trials is more difficult to detect when the encoding was only poorly done or incomplete. This assumption is based on findings from the retrospective memory literature reporting modulations of the frontal effect depending on the encoding strategy (e.g. Kounios, Smith, Yang, Bachman, & D'Esposito, 2001; Sanquist, Rohrbaugh, Syndulko, & Lindsley, 1980; Weyerts, Tendolkar, Smid, & Heinze, 1997). In our study participants had to encode one of two actions (pressing a specific letter key) and one of two cues (target colour). With a deficient encoding of the letter participants still had a 50 % chance to press the right key without explicit knowledge. Successful performance in the prospective task despite incomplete encoding seems therefore possible and this might have had an influence on the ERPs. Future studies on neural correlates of prospective memory encoding will have to further explore this possibility by distinguishing between remember- (strong recollection experience) and know-trials (weaker recollection experience) as it was suggested for episodic memory (Daselaar, Veltman, Rombouts, Raaijmakers, & Jonker, 2003). (2) Another explanation might be that late slow waves in the EEG are hard to detect and if detected hard to differentiate between electrodes (Gutchess et al., 2007). Accordingly, the

signal might be indistinct and difficult to find especially when only four (FPSW) or even only two (TPSW) electrodes can be considered. (3) A last explanation might be that the signal-to-noise ratio especially for the later unrealized intention formation trials was too low. The amount of errors participants made might not have been enough to exactly map the curve – although it corresponds largely to the amount in previous studies finding an effect (West et al., 2003a; West & Ross-Munroe, 2002). However, if our data – due to too few trials – would not have been able to differentiate between later realized and later unrealized intention formation trials the source localization with sLORETA should reveal the same pattern for these two trials. Yet, importantly, the data show a clear differentiation between these two intention formation trials with higher activations in later realized than later unrealized intention formation trials. Hence, the missing Sm effect in the ERP data might be better explained by an incomplete encoding process or general difficulties in measuring the slow waves. To further examine the former hypothesis future research should focus on differences between well-encoded versus poorly-encoded items. Moreover, difficulties arising from the latter point could be erased by using a higher density of electrodes.

Source localization.

Our first prediction – namely that age differences in prospective memory performance are also reflected in age differences in neural correlates associated with the intention formation phase – was supported by the results of the sLORETA analyses. Furthermore, the second prediction was confirmed by revealing clear evidence that adolescents and old adults differed not only from young adults but also from one another in the recruited neural resources to encode an intention successfully. For the early portion of the time frame of the N2 (N2e), old adults displayed both for ongoing activity trials as well as for later realized intention trials a higher activation in prefrontal and temporal regions compared to young adults. What differed between the two trials were the local maxima of age-related differences: For ongoing trials the maximum difference in activity was in right inferior and bilateral middle frontal areas, whereas for later realized trials the maximum was in the right middle temporal gyrus. In later unrealized intention formation trials, no differential activation in these regions was found. It seems, therefore, that young and old adults differed in very early processes that were, however, not specific processes for encoding as ongoing and later realized trials were similarly activated.

Despite a clear age-related difference in the polarity and amplitude of the late portion of the N2 (N2l), hardly any differences were found in the underlying activated regions, neither for old versus young adults nor for adolescents versus young adults. Also during the time window of the LPC there were hardly any differences between old and young adults suggesting, therefore, that similar processes are going on in these two age groups starting at 350 ms and lasting for several hundred milliseconds. Adolescents, however, displayed a clearly higher bilateral activation in the cuneus (maximum in left hemisphere) in the time window of the LPC compared to young adults and this specifically for later realized intention formation trials. This differentiation between later realized and later unrealized intention trials in the comparison of age groups seemed therefore to begin at an earlier stage for adolescents than for old adults. This was in line with the ERP findings reporting a significant difference between these two intention trials in the LPC of adolescents. The activation of the cuneus was intensified during the time window of the FPSW (maxima in right hemisphere) and expanded to middle occipital regions. It then declined during the time window of the TPSW but was still significant in the right cuneus. For later unrealized intention formation trials the only significant difference was during the time window of the FPSW in the left middle occipital gyrus. In comparison to later realized trials it seemed as if the activation in occipital regions came too late and in the wrong hemisphere. In ongoing activity trials there were hardly any differences between adolescents and young adults for all time frames. Specific differences between later realized and later unrealized trials in the comparison of old and young adults arose during the time window of the FPSW and TPSW. While no age differences were seen in later unrealized trials, old adults recruited significantly more regions in the right superior frontal gyrus compared to young adults in later realized trials. This activation was expanded to right middle and superior temporal regions during the time window of the TPSW.

Overall, results suggested that adolescents may have needed to recruit more occipital regions than young adults to successfully encode an intention that is later correctly realized. This difference in activation began at around 500 ms with a maximum in the left hemisphere, then got stronger over the next several hundred milliseconds with a maximum in the right hemisphere and declined in the time course up to 1200 ms. A higher activation in occipital regions during (successful) encoding was previously associated with a higher level of visual attention (Morcom et al., 2003) and increase in the perception and manipulation of visuospatial information (Hofer et al., 2007). Similar regions (BA 37, 19) have been found when participants maintained images of objects in working memory and

intentionally encoded objects (for a review see Cabeza & Nyberg, 2000). Therefore, it seems that if adolescents allocate more visual attention to the stimulus during encoding than young adults they may be able to encode the intention successfully. Another explanation might be that adolescents rely more on surface encoding strategies than young adults (e.g., involving visual or phonological processing). This explanation is consistent with findings from studies reporting an Sm effect in parietal and occipital cortex in non-semantic encoding tasks (e.g., syllable count Davachi, Maril, & Wagner, 2001; Otten & Rugg, 2001b). Accordingly, given that this activation emerged relatively late (starting at 500 ms), it seems plausible that this occipital activation not solely reflected a bottom-up process (early visual processing being sensitive to sensory properties) but also top-down processes which might be modulated by PFC regions (general attentional effects and mnestic representations, Hopfinger, Buonocore, & Mangun, 2000; Kim & Cabeza, 2007). This is inline with our previous assumption of adolescents compensating the limited input from prefrontal regions during encoding with a higher activation in higher sensory regions.

Old adults displayed two main differences: one early and widespread activation between 250 and 350 ms in inferior frontal and middle temporal regions that seemed similar in ongoing activity trials and later realized intention trials. The second activation begun in the right superior frontal gyrus after about 700 ms and expanded to right middle and superior temporal regions lasting up to the end of the measuring point (1200 ms). Research in retrospective memory suggests that lateral prefrontal regions support encoding by general executive and working memory processes – e.g., optimization of encoding through processes of selection, handling, and organisation of parts of the episode or generation of goal-directed signals that modulate processes in posterior sensory and association areas (Duncan & Owen, 2000; Fletcher & Henson, 2001; for a review see Lee, Robbins, & Owen, 2000). This is in accordance with previous research using event-related fMRI reporting higher activation in anterior prefrontal cortex during encoding that predict later successful retrieval (Morcom et al., 2003; Rypma & D'Esposito, 2003). It seems therefore, that old adults, in order to correctly realize the intention, needed to recruit more frontal resources during the encoding of the intention. This is in line with our assumption that old adults would be more likely to integrate new information into existing body of knowledge by retrieving memory content through activation of the PFC. Furthermore, this hypothesis seems to be supported by the late activation of right middle temporal regions (MTL) of old compared young adults. This region was associated with the binding of information through the encoding of a consistent representation of parts of the episode

(Bunge, Burrows, & Wagner, 2004; Cohen et al., 1999; for a review see O'Reilly & Rudy, 2001). It might therefore be possible that the higher activation of old adults first in the PFC followed by regions in the MTL reflects the integration of to-be remembered material into existing representations through retrieval of past episodes in the PFC and the binding of these information in the MTL.

Limitations and future directions

The present study explored neural correlates of the encoding of a delayed intention. However, the formation of a future intention in prospective memory research consists of three different components: (1) encoding a to-be remembered action, (2) encoding a stimulus, situation or time point when this action should be performed (prospective cue), and (3) encoding the intent itself. Accordingly, it might be possible that differential mechanisms are active during encoding in these three components. The paradigm we used does not allow to disentangle this influence and future research should further explore this distinction by separating the three aspects components of a prospective intention.

A possible limitation for the interpretation of electrophysiological results arises from the repetition of prospective cues with 48 prospective memory sequences overall. It is possible that the first prospective memory trials did not trigger the same processes as the last intention and that different neural processes may have been involved in the later blocks of the experimental procedure. However, only further research using within-subjects analysis over blocks with a large number of participants to enable stable signals also with fewer blocks will allow examining intra-individual differences in intention formation across task performance.

Conclusions

This study combined ERP and source localization methods to provide new insights into the temporal dynamics and neural correlates underlying age-related variation in intention formation across the lifespan. Our data revealed five ERP components differentiating between intention formation and ongoing activity trials. Source localization of these ERP components revealed an increased activity in frontal and later in temporal regions in older compared to young adults whereas adolescents showed an increased activity in occipital and parietal regions compared to young adults. Together our data support the hypothesis that age differences in prospective memory performance are associated with distinct neural correlates during the formation of intentions across the lifespan.

STUDY 3

3.3 Impact of the familiarity with the ongoing sequence on prospective memory performance in old adults

3.3.1 Introduction

Realizing delayed intentions such as to close the window before leaving the house or to blow out the candle before going to bed are essential for an autonomous and independent way of living. If such prospective intentions can no longer be executed with an acceptable accuracy assistance from third persons is needed to accomplish activities of daily living (Kliegel, Ramuschkat, & Martin, 2003; Rendell & Craik, 2000). However, there is a remarkable inconsistency regarding age differences in prospective remembering. Some studies have investigated prospective memory performance in a so-called naturalistic setting where the task had to be carried out in the everyday environment of the participant using for example instructions like to post a letter in a week from now, to return a phone call at 9 a.m. the following day, or to note periodically the time point in an organizer (e.g., Maylor, 1990; Patton & Meit, 1993; Rendell & Thomson, 1993, 1999). However, the big majority of prospective memory research has been conducted in a laboratory setting (Einstein & McDaniel, 1990; Kliegel & Jager, 2006).

In this latter setting almost all prospective memory studies report age-related differences with old adults displaying a reduced performance (for a meta-analysis see Henry et al., 2004; Mantyla & Nilsson, 1997; Park et al., 1997; West et al., 2003a; Zöllig et al., 2007) (for an exception in event-based tasks see Einstein & McDaniel, 1990; Einstein, McDaniel, Richardson, Guynn, & Cunfer, 1995). Contrary to these findings studies looking at prospective memory performance in a naturalistic setting consistently report no age-related differences or even a better performance of old compared to young adults (for a meta-analysis see Henry et al., 2004). These findings have introduced the term ‘age prospective memory paradox’ (Rendell & Craik, 2000). Various studies have tried to explain this paradox by focusing either on the age deficit in laboratory settings or on the age benefit in naturalistic settings. In the following section we give a brief outline over the most common explanatory approaches in both fields beginning with the age benefit.

Explanatory approaches for the age benefit in naturalistic settings mainly focus on two variables: motivation and external memory aids. It was suggested that the *motivation* to successfully complete a prospective task outside the laboratory might differ for young and old adults in various aspects (Patton & Meit, 1993; for an overview see Phillips et al., 2008; Rendell & Craik, 2000): from a low motivation of young adults to perform correctly (Dobbs & Reeves, 1996; Maylor, 1993), over differences in social norms and personality dimensions (Dobbs & Reeves, 1996; Maylor, 1993), to differences in lifestyle such as less structured and predictable lives of young adults (Henry et al., 2004; Maylor, 1996). However, direct manipulation of these factors in relation to age differences in prospective tasks are rare and the empirical evidence has so far not been able to consistently explain the age benefit. The use of *external memory aids* as explanatory approach for the age benefit is based on the assumption that as old adults report more memory problems in everyday life they might be more susceptible to the fallible nature of their memory and therefore are more likely to use external memory aids (Cavanaugh, Grady, & Perlmutter, 1983; Hertzog et al., 2000; Patton & Meit, 1993). In prospective memory research external cues (e.g., a note in a diary) and conjunction cues (e.g., associating an intention with a specific ongoing event like taking medication when preparing breakfast) are discussed as being an efficient way to remember intentions (Maylor, 1990). However, contrary to the widespread view, findings reveal that old adults are not more likely to use external memory aids than young adults but that they might be more efficient in applying them (Maylor, 1990; Patton & Meit, 1993; Rendell & Craik, 2000). Further research is needed, however, to test this hypothesis and investigate underlying processes.

Explanatory approaches for the age deficit respectively for differences in age effects across laboratory studies are mainly discussed in two directions: within basic cognitive functions and within the multiprocess framework. Considering basic cognitive functions it was argued that prospective memory as a high-order function is only secondarily impaired with age because it relies on *basic respectively low-order cognitive functions* that primarily decline with age (such as executive functions, episodic memory, processing speed, retrospective memory, and working memory, e.g. MacPherson, Phillips, & Della Sala, 2002). As such the decline in prospective memory is thought to be not specific (Craik & Kerr, 1996). An overlap with these low-order functions has indeed been found, however, these studies also identified unique age-related influences on prospective memory (Salthouse et al., 2004; Zeintl, Kliegel, & Hofer, 2007). Hence, this approach does not give a consistent explanation of the age deficit. The second direction focuses on the

multiprocess framework of McDaniel and Einstein (2000). This framework predicts that the magnitude of age-related differences depends on the extent to which the task relies on automatic versus strategic and resource-demanding processes. The following factors are discussed that might increase strategic demands and hence age deficits: (a) non-distinct prospective cue, (b) weak association between cue and action, (c) highly engaging ongoing task, and (d) non-focal prospective cue. By varying these factors in experimental settings age-related differences could be manipulated (for an overview see McDaniel, Einstein, & Rendell, 2008). Although this framework mainly focused on explaining age-related differences within differential effects in laboratory studies, it was also suggested that these factors might help to explain the age prospective memory paradox. However, for a consistent explanation findings are needed that show the demands of naturalistic settings relying mostly on automatic processes whereas the demands in laboratory settings rely on strategic ones. So far, this has not been tested.

In summary, research on explanatory approaches for the age prospective memory paradox is scarce and focuses on one of the two aspects of the age paradox at a time – either decline or benefit. Accordingly, as Phillips et al. (2008) recently pointed out studies are needed that vary specific aspects of task setting and nature of task in a more methodological manner. In the present study, we therefore manipulated an aspect of familiarity in a matched sample while keeping the task complexity and task setting the same. The idea for the manipulation is based on the assumption that whereas old adults are familiar with the course of events in their daily life this sequence is completely unpredictable in the laboratory. An analogy would be a bus ride in a familiar town where stations are known and monitoring of the target destination is at a minimum level compared to a bus ride in an unfamiliar city where monitoring for the destination requires more resources and missing the station is more probable. The demands in these two settings (familiar vs nameless town respectively naturalistic vs laboratory task) to successfully complete a prospective task might therefore not be the same and the performance outcome might not be directly compared. We would therefore suggest that the reason for the poorer performance of old adults in laboratory settings may be founded on the one-sided higher demands of the prospective task. Accordingly, the hypothesis would be that if old adults are given the chance to familiarize themselves with the sequence of events coming up in the laboratory task and hence start with the same ‘knowledge’ as in naturalistic tasks they would show a better performance. If this were true, we would have to contradict the age prospective memory paradox as findings are not paradoxical between

the two settings but in fact depending on the amount of familiarity with the ongoing sequence.

To test our hypothesis we developed a paradigm that allowed the learning of sequences of events and applied it within a between-subjects design. Outcome variables were measured using behavioural and electrophysiological data. In accord with previous research (for an overview see West, 2008) we focused on three modulations of ERPs that differentiate ongoing activity from prospective trials and take these as time windows for the source localization with sLORETA: N300, parietal positivity (PP), and frontal slow wave (FSW). The amplitude of all three ERPs is found to be bigger for correct than incorrect prospective trials indicating that they are associated with successful prospective memory (West & Ross-Munroe, 2002).

The *N300* reflects a negativity over occipito-parietal regions of the scalp emerging between 200 and 400 ms after stimulus onset (West et al., 2003a; West et al., 2001; West & Ross-Munroe, 2002). Findings suggest that the N300 is associated with processes underlying the detection of prospective cues (West & Ross-Munroe, 2002). The amplitude is reduced in older adults (West & Covell, 2001; West et al., 2003a), and this reduction appears to result from the failure of older adults to recruit controlled attentional processes that facilitate cue detection (West & Bowry, 2005).

The *FSW* reflects a sustained positivity over frontal regions of the scalp emerging approximately 400 ms after stimulus onset. The functional significance of this modulation is not yet clearly understood, but two possibilities are discussed. First, findings suggest that it might reflect a neural generator that coordinates the disengagement from the ongoing activity (West et al., 2000; West & Ross-Munroe, 2002) by actively shifting the attention from one task to the other (Cockburn, 1995). A second functional significance of the FSW might be an evaluation of recovered information from memory (Einstein & McDaniel, 1996; West & Ross-Munroe, 2002). This is similar to findings in retrospective memory literature (recognition) associating the frontal slow wave with the activity of post-retrieval processes that use recollected information to guide task performance (Allan & Rugg, 1998). Regarding age differences findings are ambiguous with two studies finding a reduced amplitude in older adults (West & Covell, 2001; West et al., 2003a) and one study reporting an elevated FSW (West & Bowry, 2005).

The *PP* reflects a positivity that is broadly distributed over the central, parietal, and occipital regions of the scalp (West & Covell, 2001) and emerges between 400 and 1200 ms. The PP reflects two distinct components. The first is associated with the retrieval of a

prior episode from memory and is common to prospective memory and explicit episodic memory (e.g., recognition or cued-recall, West & Krompinger, 2005). The second appears to be more unique to prospective memory and may be related to post-retrieval processes that serve to coordinate the prospective and ongoing components of the task after a cue is detected and an intention is retrieved from memory (West & Krompinger, 2005). The effects of aging on the PP have been somewhat mixed in previous research with two studies revealing little or no effect of aging (West et al., 2003a; Zöllig et al., 2007) and two revealing a clear decrease in the amplitude in older adults (West & Bowry, 2005; West & Covell, 2001).

What we expected from the training were effects both in behavioural as well as in neurophysiological findings. From a behavioural perspective results indicate that old adults tend to have fewer correct responses and show longer reaction times in comparison to young adults (for a review see Henry et al., 2004; West & Bowry, 2005). They also were reported to show more false alarms (Einstein et al., 1998; Zöllig et al., 2007). Hence, we expected the training group to show a faster reaction time and a higher accuracy in their responses regarding both correct prospective trials as well as fewer false alarms. Considering the ERP data we expected that the training group approximates the pattern of young adults by showing a higher N300. The FSW and PP findings are inconsistent. But based on the nature of the prospective task and training we expected that both modulations might be influenced through our intervention. In the source localization analyses we expected that the control group need more resources to correctly perform the prospective task. Differences were supposed to arise in the network associated with prospective memory (for an overview see both Burgess et al., 2008; West, 2008) – mainly prefrontal areas in early and more parietal areas in later processes.

3.3.2 Method

Participants

Forty old adults (age range: 69 – 83 years) participated in the study. Data from one person was excluded from the analyses due to a high level of artefact in the EEG. Hence, the training group consisted of 19 participants (9 f; age: M = 74.7 years, SD = 4.19; education: M = 13.6 years, SD = 2.61) and the control group of 20 (10 f; age: M = 75.7, SD = 4.33; education: M = 14.1 years, SD = 2.47). All participants were right-handed according to their score on the Edinburgh-Handedness-test (Oldfield, 1971) and had normal colour

vision measured with the Ishihara test of colour blindness (Ishihara, 1960). They were in good health and none reported brain injuries, psycho-affective medication, drug consumption, or other diseases affecting brain functioning. Participants were individually matched in pairs and randomly assigned to either of the training or control group considering the following variables: age, education in years, and gender. A standard psychometric testing battery consisting of psychomotor speed, memory span, mental flexibility, perceptual and motor skills, and verbal intelligence was performed; for one to exclude participants scoring one standard deviation or below age appropriate norms and for the other to control that group means did not differ in these variables. Participants were recruited at a lecture for senior citizens at the University of Zurich or consisted of registered persons in our database being interested in a research project. All individuals were paid 30 CHF for their participation and were provided with written and oral descriptions of the study before written informed consent was obtained. The experiments were conducted in agreement with the declaration of Helsinki.

Materials and Procedure

The paradigm consisted of a total of 180 trials that were presented in one block. Stimuli appeared in a table of 30 fields arranged in a 6 x 5 matrix and were composed of black capital letters on a coloured background either in yellow, green, orange, turquoise, magenta, violet, red, or blue. Each letter was presented for a minimal duration of 1.5 s and a maximal of 2 s. If participants responded earlier than these two seconds the next letter appeared without an inter-stimulus interval. If they took longer than 2 s a blank table was presented until a response was given.

Characteristically for a prospective memory task participants had to work on two tasks concurrently: ongoing and prospective task. *Ongoing task.* The ongoing activity consisted of a 2-back task. The principle of this task is that participants use their working memory to memorize the identity or location of a consecutive series of stimuli and indicate each time if the currently presented stimulus appeared already n-steps before. The stimuli in our paradigm are the letters regardless in which field they appear and what background colour is presented. Hence, in a sequence of letters those are labelled targets that appeared already two letters before and require a ‘yes’-response, all others are non-targets requiring a ‘no’-response. Reactions were given by using the right middle and index finger. *Prospective memory task*. The prospective cue which is embedded in the ongoing activity consisted of two specific background colours: red and blue. Participants should detect

these cues during conducting the ongoing task and react to it by suppressing the 'yes-or-no' response and instead press a third key ('x') using the left index finger. To give the responses a keyboard was used on which a cover was applied leaving visible only the three keys ('yes', 'no', 'x') with an explicit identification so as to prevent confusing of finger positions. The stimuli had the following distribution: 53 % non-targets (96 trials), 30 % targets (54 trials), and 17 % prospective cues (30 trials). Before the experimental blocks, participants performed two practice blocks, each repeatable until the task was fully understood. The first block followed the instruction of the 2-back ongoing task and contained 15 trials with four targets. The second block started after the prospective memory instructions were explained and consisted of 18 trials with five targets and three prospective cues. Participants were encouraged to ask questions during and after the practice blocks to ensure that they understood the instructions before the experimental blocks began. After the prospective experiment an ongoing pure block was applied consisting of 60 trials (18 targets, no prospective cue) serving as baseline for the later calculation of the prospective interference effect (i.e., task costs) stating that the addition of a prospective memory component can influence performance in the ongoing task (Marsh et al., 2003; Smith, 2003). Participants were instructed accordingly that no prospective cue will be presented.

Most importantly for the aim of our study are the fix sequential positions in which the variable letters of the ongoing task were presented. Six different sequences were used consisting each of six different positions in the matrix. Every sequence was repeated five times and in a consecutive order (sequence one, sequence two, etc.). They had a fix starting point in one of the six fields on the far left of the matrix (sequence one in the field top left, sequence two in the following field below, etc.) rendering it easier for the training group to learn and assign the different sequences. Two of the sequences – namely number two and six – are displayed in Figure 12. One prospective cue was comprised in every sequence and presented in a random but fix order, i.e., the amount of ongoing trials differed between prospective cues.

Characteristics of training and control group

Training group. During the training session participants learned the six sequences by memorizing both the consecutive positions and colours of the respective six stimuli. In addition to the distinct starting position the sequences were chosen so as to resemble a figure which should support the learning. Hence, at the beginning of training every

sequence was presented along with a simple black-and-white figure representing the sequence (e.g. umbrella, kink, etc.; see Figure 1). Participants were told to ignore the letters for now, but they were displayed nonetheless to prevent confusion when the task started. The training was applied in a two step procedure: first on paper sheets and then on the computer. The training on paper sheets started with the naming of colour and tipping of positions first on a colour print-out and then on a blank matrix. The training on the computer was similarly conducted and training criteria was met by a twofold reproduction of the six sequences on a blank matrix on the computer screen with only one error in position and as much correct colour naming as possible (criteria for colour naming was non-rigid as it emerged to be too difficult for the relatively short training duration of 45 minutes). Most importantly, participants received the instructions for both the ongoing and prospective task only after completing the training. Their sole benefit should be the knowing of the sequence of events and not other factors like a higher familiarity with the prospective cues, prior knowledge of the ongoing activity, or more time to plan the tasks. After the experiment participants were asked to tip again the six sequences on a blank matrix and name the corresponding background colour.

Control group. To ensure that the cognitive exposure was similar to the one of the training group both in demand and time the control group performed parts of the Wechsler-Memory-Scale (WMS-R, Härting et al., 2000): logical memory and visual- and verbal-paired associates.

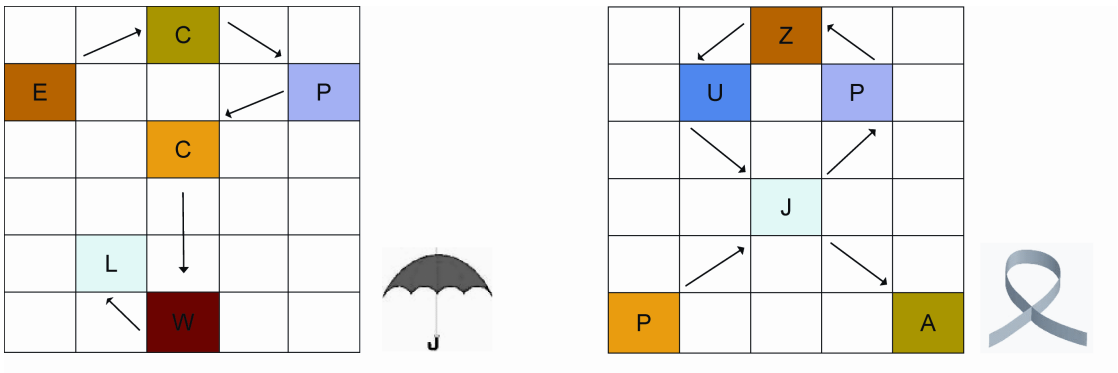

Figure 12. Illustration of the prospective memory paradigm used in the present study. Displayed are two of the six sequences (namely sequence 2 and 6) including the image used for illustration. Note that the arrows mark the order of the stimulus appearance.

Recording and analysis of electrophysiological data

Recording. The electroencephalogram (EEG) was continually recorded while participants performed the task. The EEG was amplified with a QuickAmpMR (Brain Products GmbH), digitized at 500 Hz, and recorded with a 16 bit A/D converter. During recording no filter was applied (BrainVision Recorder Software). The EEG was recorded from an array of 42 Ag/AgCl scalp electrodes which were placed according to the 10-20 system being sewn into an EasyCap or affixed to the skin with an adhesive patch (Fp1, Fp2, Af3, Af4, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC3, FCz, FC4, FT8, T7, C3, Cz, C4, T8, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, Po7, Po3, Po4, Po8, O1, Oz, O2, Veog, Heog). Vertical and horizontal eye movements were recorded with the two bipolar electrodes – one placed above and below the left eyes and the other on the temples. During recording inter-electrode impedances were maintained below 10 kΩ and a common reference was used.

Processing. The recorded EEG was bandpass-filtered (.1-30 Hz, time constant 1.59155s, 48 dB/oct). ERP analysis epochs were extracted off-line and included a 200 ms of pre-stimulus baseline and 1200 ms of post-stimulus activity. Ocular artefacts associated with blinks, as well as additional eye movements and articulated muscular artefacts were corrected using independent component analysis (ICA; Vision Analyzer software, Brainproducts GmbH). This method separates the mixture of independent EEG signals into 42 factors (corresponding to the number of electrodes used) by conducting a component analysis. Jung et al. (1998) demonstrate that the unwanted artefacts will be contained in one or more components that can be removed and the artefact free EEG reconstructed from the remaining components. To identify the ocular components we compared the timing and topographical distribution of the artefacts in the EEG against that of the independent components. Following ocular correction, trials contaminated by remaining artefacts were rejected with the Raw Data Inspector (Vision Analyzer software, Brainproducts GmbH).

ERPs were averaged for the following artefact free trials that elicited a correct response: (1) *Non-target trials* (training group: M = 56.7, SD = 22.5, range = 18-90; control group: M = 48.4, SD = 18.7, range = 14-80), (2) *Target trials* (training group: M = 34.7, SD = 10.6, range = 11-51; control group: M = 34.8, SD = 8.9, range = 10-47), (3) *Prospective trials* (training group: M = 27.5, SD = 1.1, range = 25-30; control group: M = 25.6, SD = 4.1, range = 16-30). ERPs were not averaged for prospective trials that elicited a wrong response given the relatively low number of these trials.

Analysis of mean amplitude. ERPs were quantified in measures of mean amplitude over latency windows where modulations of interest were observed relative to mean voltage of the 200 ms pre-stimulus baseline activity. The following three ERPs were considered for analyses: (1) *N300:* negativity between 200-250 ms after stimulus onset, recorded at electrodes O1, Oz, O2, Po7, and Po8; (2) *PP:* prospective positivity between 720-750 ms after stimulus onset, recorded at electrodes Cp3, Cp4, P3, and P4; (3) *FSW:* frontal slow wave between 700-800 ms after stimulus onset, recorded at electrodes F1, F2, F3, and F4. The selection is based on findings from previous research considering information of topography, electrode choice, and time window (West & Covell, 2001; West et al., 2003a; West et al., 2000; West & Krompinger, 2005).

sLORETA analysis. Standardized low-resolution electromagnetic tomography (sLORETA) was performed on the basis of the scalp-electrode electric potential distribution (Pascual-Marqui, 1999, 2002; Pascual-Marqui et al., 1994) to localize differential neural recruitment between groups and conditions. sLORETA was used to estimate the three-dimensional intra-cerebral current density distribution in 6239 voxels with a spatial resolution of 5 mm and a voxel volume of 0.125 cm^3. The evaluated ERPs were subjected to a sLORETA analysis. The obtained images were compared on a voxel-wise basis for inter-group differences between control and training groups in correct non-target, target, and prospective trials.

Two time frames of interest were defined based on the temporal windows of the analysed ERPs (200 – 250 ms and 700-800 ms). The time window of the PP was not analysed separately given that it is part of the time window of the FSW and revealed no further information. The statistical comparisons were conducted using *t*-tests for independent samples corrected for multiple comparisons (Nichols & Holmes, 2002). These patterns of descriptive *p*-values were plotted in statistical probability maps (SPM). sLORETA values were transformed logarithmically to achieve normal distribution. No normalization was applied.

3.3.3 Results

Results focus on differences between control and training group in performance on the prospective memory tasks and age-related differences in neural recruitment for successful prospective remembering. Effect size is reported as correlation coefficient *r* and the widely accepted suggestions from Cohen are used for interpretation (1988; 1992). The behavioural data were analyzed by using analysis of variance (either multi- or univariat). If normal

distribution and/or variance homogeneity could not be assumed, non-parametric tests were applied using the Mann-Whitney *U*. The ERP data were analyzed by using the multivariate *F*-ratio (repeated-measures MANOVA). The Greenhouse-Geisser correction was conducted if sphericity could not be assumed and epsilon (ε) is reported as a value of correction. One-tailed significances are reported when the direction of the effect was in the hypothesized direction, they are labelled with '(one)' followed by the exact p-value.

Behavioural data

Accuracy. Response accuracy and inferential statistics for the effect of group on non-target, target, and prospective trials are presented in Table 6. The data for non-target trials were separated into 'correct' responses and 'false alarm' (target reaction in a non-target trial), those for target trials were separated in 'correct' and 'false' (non-target reaction in a target trial) responses, and those for prospective trials in 'correct' and 'false' (non-target or target reaction in a prospective trial) responses as well as 'false alarms' (prospective reaction to a wrong cue in a non-target or target trial). As expected, the training group made significantly fewer prospective false alarms than the control group suggesting that if they reacted they reacted correctly. The amount of correct prospective trials goes in the right direction with the training group having a higher score and showing a more consistent responding (smaller intra-group variance), however, this measure did not reach significance. There was a tendency for the training group to have a higher amount of correct responses in non-target trials. They did not differ in any other ongoing task measure.

Reaction time. The mean response time data and inferential statistics for control and training group in correct non-target, target, and prospective trials are presented in Table 7. The training group is significantly faster to react correctly to prospective cues than the control group. Groups did not differ in their reaction time in correct non-target and target trials. The main effect of conditions was significant with the fastest reactions to prospective trials, followed by reactions to target trials and slowest was the response in non-target trials. This slowest reaction time in non-target trials might reflect different monitoring processes going on looking for target and prospective trials and the inhibition of both of these reactions when no according stimulus is present.

Prospective interference effect (task costs). The inferential statistics regarding the task costs in accuracy and reaction time in correct non-target and target trials are displayed in Table 6 respectively 7. Results reveal that the inclusion of the prospective task requires

Table 6. Mean accuracy for training and control group presented at proportions.

		Group		Main Effect	Effect size (r)
Paradigm		Training	Control		
NT: correct	*M*	90.02	83.80	*128.0 °*	.28
	SD	9.77	14.58	*(p>.081)*	
NT: false alarm	*M*	8.17	12.14	*137.5*	.24
	SD	9.48	12.88		
T: correct	*M*	65.89	67.04	.04	.03
	SD	18.61	17.89		
T: error	*M*	35.37	31.67	.40	.10
	SD	17.85	18.76		
PM: correct	*M*	95.10	89.00	*165.5*	.11
	SD	3.58	14.13		
PM: error	*M*	4.90	10.50	*176.5*	.06
	SD	3.58	13.93		
PM: false alarm	*M*	0.73	2.07	*122.0 **	.32
	SD	0.97	2.59		
Ongoing pure					
NT: correct	*M*	93.97	88.54	*154.0*	.16
	SD	6.62	13.68		
T: correct	*M*	83.93	85.53	.20	.07
	SD	10.30	11.69		

Task costs	Main effect: condition		Main effect: group (based on difference score)	
NT: correct	*Wilcoxon, Z (r)*	5.44 *** (.87)	*Mann-Whitney, U (r)*	171.5 (.08)
T: correct	*Paired t-test, t (r)*	13.78 *** (.91)	*t-test, t (r)*	.56 (.09)

Inferential statistics are presented as the F-ratio or U (italics) from Mann-Whitney. T = target, NT = non-target, PM = prospective memory. ****p* <.001, **p*<.05, °*p*<.10.

further cognitive resources as both measures (accuracy and reaction time) score higher when only the ongoing task must be performed. Importantly, there was no interaction with group, i.e., they did not differ in the amount of task costs in either variable. This suggests that the ongoing task is not per se easier for the training group.

Sequence retrieval. The training group tipped an average of five out of six stimuli positions in each sequence correctly. The score varied for the different sequences and ranged from 4.1 – 5.7 correct positions. As expected, the un-cued naming of the correct colour was much more difficult and participants named an average of 0.7 out of six colour

Table 7. Mean response time (in ms) for training and control group.

		Group		Main effect: group	Main effect: condition
Paradigm		Training	Control	F-value (r)	F-value (r)
NT: correct	*M*	1768	1794	.05 (.00)	95.17*** (.85)
	SD	376	316		a,b,c
T: correct	*M*	1583	1545	.13 (.00)	
	SD	321	322		
PM: correct	*M*	1077	1207	4.08* (.32)	
	SD	239	155	(one; p = .051)	
Ongoing pure					
NT: correct	*M*	1341	1303	.12 (.05)	
	SD	324	348		
T: correct	*M*	1199	1198	.00 (.00)	
	SD	258	234		

Task costs	Main effect: condition Paired t-value (r)	Main effect: group (based on difference score) F-value (r)
NT: correct	12.72 *** (.90)	.77 (.14)
T: correct	11.11 *** (.87)	.31 (.09)

a, b, c = paired comparisons between conditions were all significant at p < .001 (Bonferroni adjusted for multiple comparisons). T = target, NT = non-target, PM = prospective memory. *p<.05, ***p<.001.

correctly. No participant of the control group reported having detected a sequence in the stimuli presented despite the repetition of the sequences.

Electrophysiological data

ERPs.

Neural activity associated with the learning of sequences was examined by comparing training and control group in the ERPs elicited in correct non-target, target, and prospective trials. Three modulations of interest were observed that differentiated between conditions (i.e., N300, PP, FSW). Figure 13 presents the different grand averaged ERPs for these three trials at selected electrode locations and the topography of these modulations are portrayed in Figure 14 (the time window of the PP is not displayed separately given that it is part of the time window of the FSW and revealed no further information). Table 8 summarizes the mean amplitude in microvolt for conditions and groups.

N300. The N300 was quantified as the mean amplitude between 200 and 250 ms at electrodes O1, O2, Oz, Po7, and Po8 in a 2 (group) x 3 (condition) repeated measures MANOVA. The main effect of condition showed a trend, $F(2,74) = 2.64$, $p > .07$, $r = .26$, reflecting greater negativity for prospective trials followed by non-target trials and with the smallest amplitude in target trials. The main effect of group was not significant, $F(1,37) = 2.29$, $p > .14$, $r = .24$. Importantly, the group x condition interaction was significant, $F(2,74) = 3.68$, $p < .05$, $r = .30$. Follow-up analyses of this interaction looking at group differences in each condition (MANOVA) revealed a trend for the training group to have a higher amplitude in non-target trials, $F(1,38) = 3.27$, $p > .078$, $r = .28$, and a significantly higher amplitude in prospective trials, $F(1,38) = 3.63$, $p < .05$ (one; $p = .065$), $r = .30$. No group difference was found in target trials, $F(1,38) < 1.0$, $p > .58$, $r = .09$. The fact that the amplitudes of prospective and target trials are almost the same in the control group ($p > .99$) whereas they are significantly different in the training group ($p < .05$; see Table 3) might suggest that participants in the former group react similarly to targets from prospective and ongoing trials whereas the latter clearly differentiate between these two targets. Variables electrode and hemisphere were left out in order to be able to include Oz in the analyses and because analyses including these variables revealed no relevant effect regarding group differences.

PP. The PP was quantified as the mean amplitude between 720 and 750 ms at electrodes Cp3, Cp4, P3, and P4 in a 2 (group) x 3 (condition) x 2 (electrodes: Cp3-Cp4, P3-P4) x 2 (hemisphere) repeated measures MANOVA. The main effect of condition was significant, $F(2,74) = 4.68$, $p < .05$, $r = .34$. Paired comparisons (corrected for multiple comparisons with Bonferroni) revealed a significantly higher amplitude in prospective trials compared to non-target trials ($p < .05$), target trials were in between the two and differed from neither of it significantly ($p > .05$). The main effect of group reached trend level, $F(1,37) = 3.68$, $p > .62$, $r = .30$, with the training group showing a higher amplitude. The group x condition interaction was not significant, $F(2,74) < 1.00$, $p > .46$, $r = .15$, nor any other analyses involving the group variable.

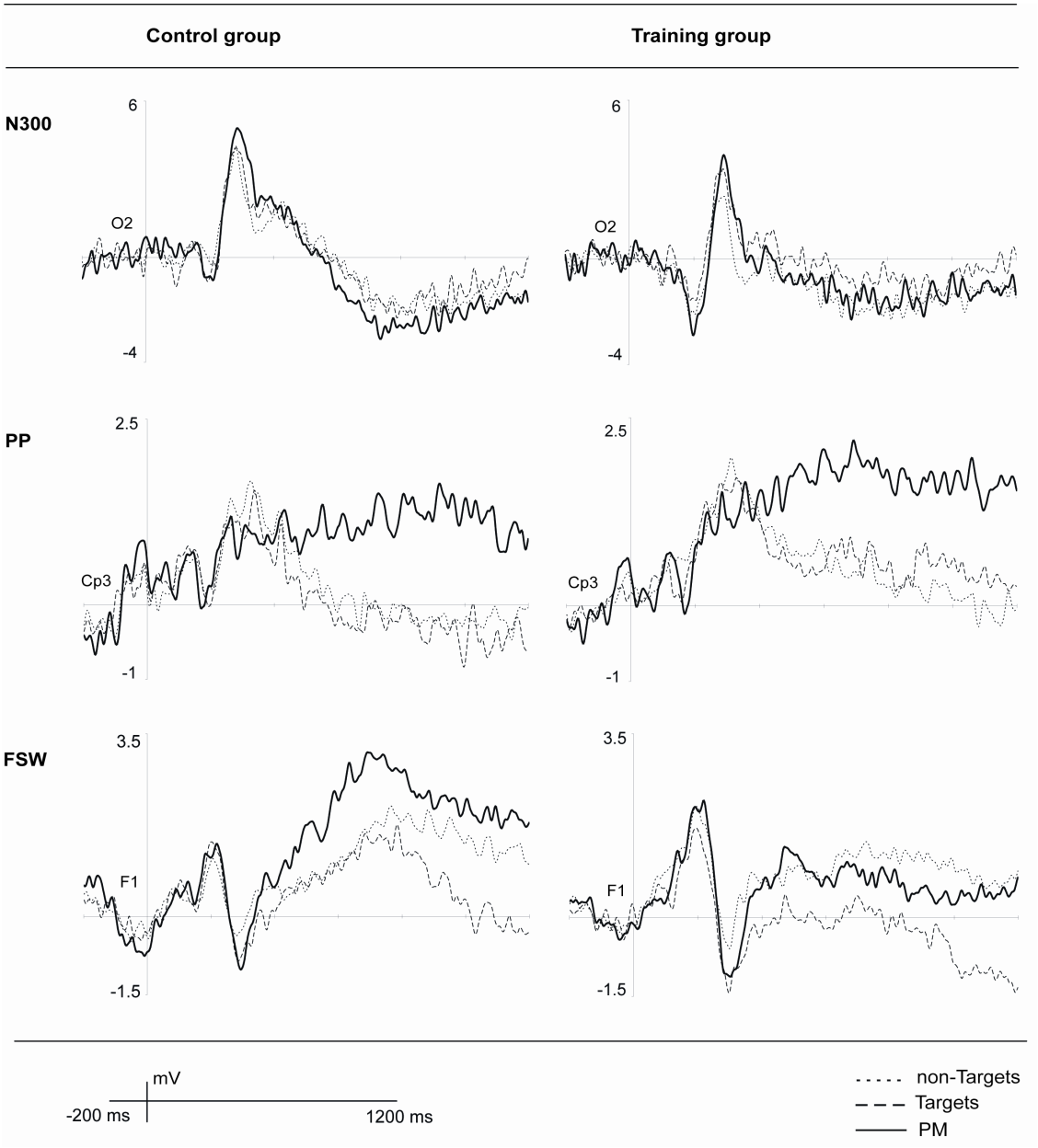

Figure 13. Grand-averaged event-related brain potentials at selected electrodes demonstrating the N300, PP, and FSW for non-target, target, and prospective trials in the training and control group.

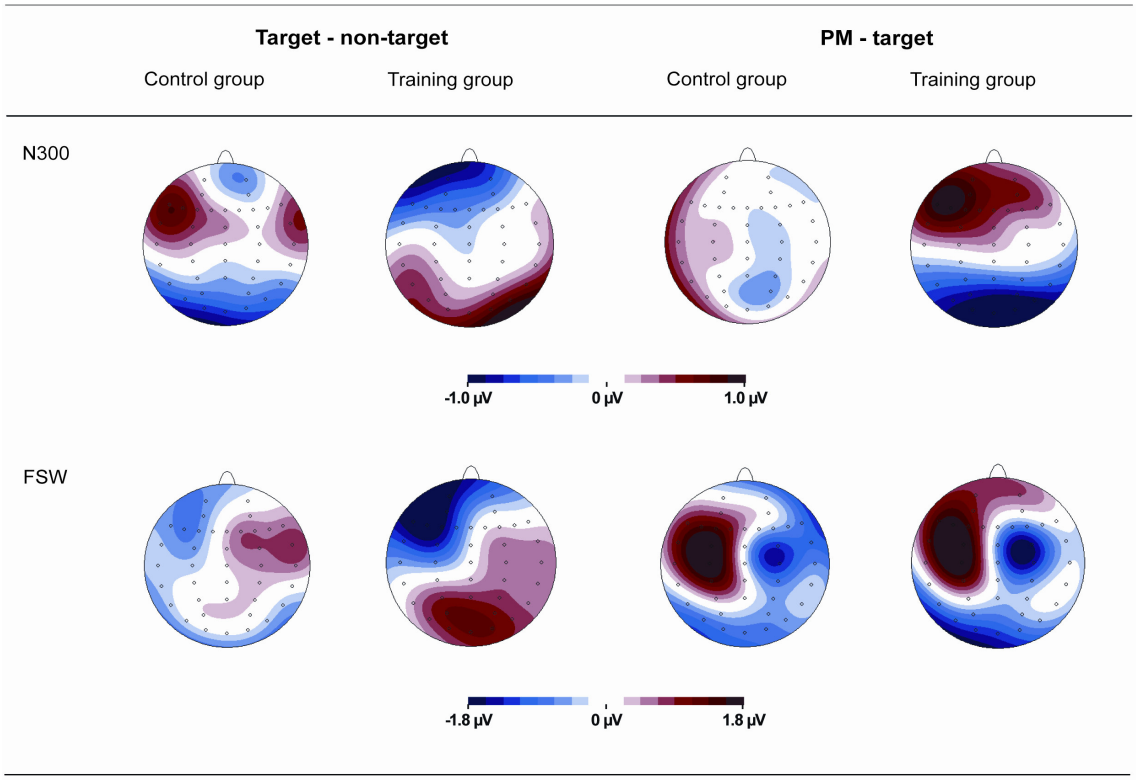

Figure 14. Topographical maps of the training and control group representing differences between target and non-target trials and differences between prospective and target trials during the time windows of the N300 and FSW.

Table 8. Mean amplitude in microvolt for non-targets, targets, and prospective (PM) trials for modulations of interest in the control and training group.

			Condition		
			non-target	target	PM
N300	Control	*M (SD)*	.469 (2.44)	-.028 (2.45)	.044 (2.42)
	Training	*M (SD)*	-1.064 (2.85)	-.468 (2.61)	-1.528 (2.74)
PP	Control	*M (SD)*	-.339 (.79)	-.156 (1.15)	.029 (1.45)
	Training	*M (SD)*	.016 (.78)	.626 (1.37)	.758 (1.52)
FSW	Control	*M (SD)*	1.676 (1.13)	1.803 (1.95)	2.346 (2.11)
	Training	*M (SD)*	1.165 (1.11)	.520 (1.17)	.677 (1.30)

FSW. The FSW was quantified as the mean amplitude between 700 and 800 ms at electrodes F1, F2, F3, and F4 in a 2 (group) x 3 (condition) x 2 (electrodes: F1-F2, F3-F4) x 2 (hemisphere) repeated measures MANOVA. The condition x group interaction reached a trend level, $F(2,74) = 2.76$, $p > .069$, $r = .26$. Follow-up analyses of this interaction looking at group differences in each condition (MANOVA) revealed a significantly higher amplitude of the control group in target trials, $F(1,38) = 6.13$, $p < .05$, $r = .38$, and still more pronounced in prospective trials, $F(1,38) = 8.78$, $p < .01$, $r = .44$, compared to the training group. No group difference was found in non-target trials, $F(1,38) = 2.03$, $p > .16$, $r = .23$. The main effect of group was significant, $F(1,37) = 8.65$, $p < .01$, $r = .43$, with the control group displaying a higher amplitude than the training group. The only other relevant effect to be significant was the electrode x group interaction, $F(1,37) = 11.52$, $p < .01$, $r = .49$. Whereas the training group had a similar amplitude over both regions ($p > .49$; fronto-central .76 mv and lateral frontal .82 mv) the control group displayed a clearly elevated amplitude over fronto-central regions ($p < .01$; fronto-central 2.16 mv and lateral frontal regions 1.71 mv).

Source localization data (sLORETA).

Source localization was performed to investigate differences in neural recruitment between training and control group in the time frames of the N300 and FSW. The control group provided the baseline for the paired comparisons, as in this group the underlying neural generators are assumed to be the 'normal' non-trained standard in healthy older adults. The statistical probability maps from the sLORETA analyses with the local maxima of inter-group differences in the three-dimensional current density distribution for correct non-target, target, and prospective trials are displayed in Figure 15. Table 9 summarizes the brain regions that demonstrated differential activation across the groups and includes X, Y, Z-MNI coordinates and the *t*-value at the local maxima. *N300 time frame*. The control group showed a higher activation in the prospective as well as in the target condition compared to the training group but with a different activation pattern. Whereas in the target condition a higher activation was found in the left middle frontal gyrus, a higher activation bilaterally in the superior frontal gyrus was displayed in the prospective condition. In the non-target condition no significant group difference was found. *FSW7PP time frame*. The control group had a clearly higher bilateral activation in the precuneus and cingulate gyrus as well as a higher activation in the left inferior frontal gyrus. For the non-target and target trials there were no significant group differences.

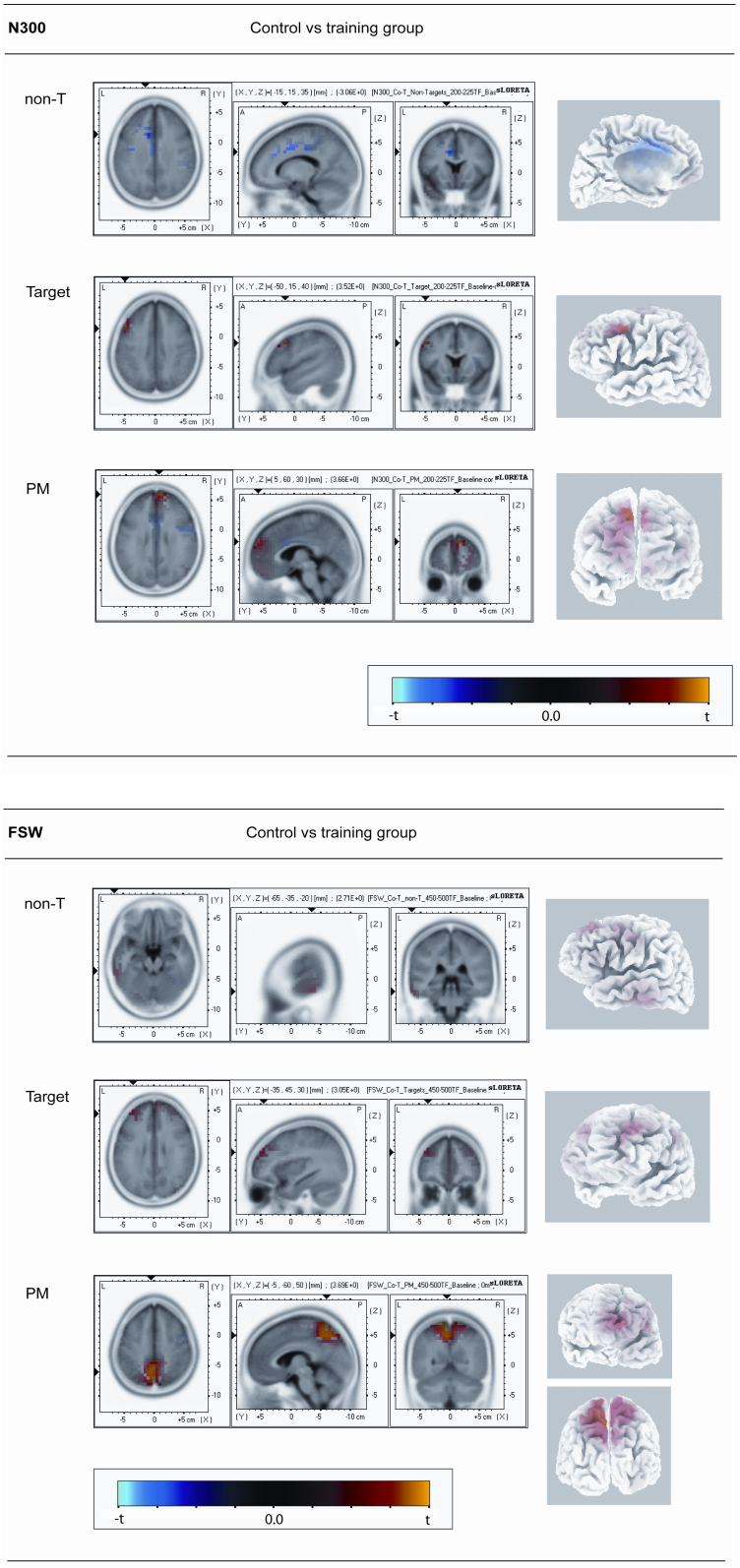

Figure 15. Statistical probability maps (SPM) of the source localization with sLORETA for differences between training and control group during the time window of the analyses ERPs. Results are significant at the $p < .05$ level (blue colour = significantly lower current density, red colour = higher current density).

Table 9. Local maxima in current density differences between control and training group calculated with standardized low-resolution electromagnetic tomography (sLORETA).

		Brain region (control – training)	HS	MNI coordinates			$t_{X, Y, Z}$
				X	Y	Z	
NT	N300	Cingulate gyrus (BA 32)	L	-15	15	35	-4.35
	FSW/	Middle temporal gyrus (BA 21)	L	-65	-35	-20	4.38
	PP	Superior frontal gyrus (BA 8)	L				
T	N300	Middle frontal gyrus (BA 9, 8)	L	-50	15	40	4.32*
	FSW/ PP	Middle frontal gyrus (BA 10)	L	-35	45	30	4.40
PM	N300	Superior frontal gyrus (BA 10, 9)	M	5	60	30	4.41*
	FSW/	Precuneus (BA 7), cingulate gyrus (BA 31)	M	-5	-60	50	4.33*
	PP	Inferior frontal gyrus (BA 45)	L				

T = targets, NT = non-targets, PM = prospective memory. *p<.05

3.3.4 Discussion

The current study sought to examine a possible explanation for the age prospective memory paradox by applying a sequence training in a laboratory setting. The idea derived from the fact that old adults know the sequence of events occurring in their everyday life and are, hence, able to plan their intentions according to other events coming up during the day. In laboratory, however, this knowledge is not given and accordingly older adults would need further resources to compensate for that missing knowledge. Reciprocally, we hypothesized that if this knowledge of sequences of events occurring is given to old adults in a laboratory setting this might boost their performance. Analyses of behavioural, ERP, and sLORETA data support the conclusion that old adults might profit specifically from the training of sequences.

Behavioural data

Response accuracy and reaction time analyses revealed that the training group profited from the sequence learning in a specific way resulting in fewer false prospective alarms and faster correct reactions. Hence, they seem to differentiate ongoing and prospective cues more reliably and once a latter cue is detected react more quickly. We

would also have expected a higher score on correct prospective trials in the training group. However, there was no significant difference between groups. The reason for this might be founded on the relatively short duration of the training and the possibly restricted effect of it as the sequences were not learned to completeness (only information of position and not colour was learned to criteria). The direction, however, was correct with the training group displaying a higher amount of correct reactions and high intra-group consistency of responding (small variance). This suggests that more intensive training with the learning of all information of the sequence might achieve a significant difference in correct prospective trials.

Analyses of the prospective interference effect revealed that the prospective memory load had a significant effect on response accuracy and reaction time of the ongoing activity both in non-target and target trials. This is in accordance with previous findings stating that the addition of a prospective memory component can influence performance in the ongoing task (for an example see Marsh et al., 2003; Smith, 2003; Smith & Bayen, 2005). Regarding group differences, however, there was only a trend for the training group to have a higher amount of correct non-target reactions in the prospective task block. All other variables including task costs were not significant between groups. Importantly, these findings support the hypothesis that the sequence training has a specific influence on the prospective task and does not get effective through a reduction in the ongoing task demands which might only secondarily enable a better prospective memory performance.

Neurophysiological data

ERPs. The evidence from the behavioural data suggesting a more reliable cue differentiation and detection in the training group is supported by findings from the analyses of the *N300*. Consistent with our expectation the training group had an elevated amplitude in prospective trials and clearly differentiated between prospective and target trials, whereas the control group's amplitude was reduced and did not differentiate between the two trials. Furthermore, the topography of the training group strikingly resembles the topography of untrained young adults in the study of West and Covell (2001), whereas the topography of the control group is comparable to the one found in untrained old adults. This suggests that the control group might specifically have difficulties in differentiating the two targets during processes of cue detection. However, in the ERP analyses they react correctly in both trials (target and prospective) and that suggests that they might need

further resources to distinguish between the two different targets which have not been detected with the ERP analyses over occipito-parietal regions but with the source localization using sLORETA. Hence, the normally and consistently reported reduction of the N300 could be influenced by the training of sequences assimilating the manifestation of young adults. The *FSW* was associated with a higher positivity when a prospective cue was present compared to the ongoing activity (West & Ross-Munroe, 2002). For the control group this picture emerged both in comparison with non-target and target trials. The latter two showing the same pattern until 800 ms and divide than with non-target trials being now similar to prospective trials. In the training group, however, another picture emerged with prospective and non-target trials showing the same pattern beginning at 400 ms. Accordingly, both non-target as well as prospective trials differed significantly between groups with the control group displaying a higher amplitude. It was previously expected that processes associated with the FSW (disengaging from the ongoing activity and evaluating the presented information) might be influenced through the sequence training as participants might have expected that a stimulus appears and anticipated the functions. This is supported by the finding of a clear distinction between target and prospective trials in the N300. Correspondingly, it can be assumed that for a successful performance – which is the case in our trials – the control group would need more resources to inhibit the ongoing task and shift the attention. This might have resulted in a higher amplitude of the FSW in the control group – this is also consistent with findings revealing a larger amplitude when retrieval of the intention is made more demanding (West et al., 2003b). However, the pattern of the control group resembles that of young adults which was thought to be the high-functioning baseline (West et al., 2003a). It is therefore difficult to conclude from a higher or lower amplitude on the effectiveness of the underlying functions. Again, the analyses with sLORETA can reveal further information in this point by calculating the sources of activation and differences between groups. The *PP* in both groups was only marginally manifested, probably due to the uncomplicated demand on retrieval processes as only one response button was possible. There was no group difference in this ERP. However, the two slow waves FSW and PP emerged in the same time window suggesting that associated processes are simultaneously activated. It seems therefore possible that these two components overlapped and influenced each other's amplitude making it harder to detect and differentiate them (for a similar problem see Gutchess et al., 2007). Hence, group differences found in the FSW respectively the absence of it in the PP might not mirror group differences in the associated processes. The

source localization of the time window including these two components with sLORETA was indeed able to distinguish the influence of these two processes and extract group differences.

sLORETA. As expected, for both analysed time windows (N300 and FSW / PP) the control group displayed a higher activation than the training group that is in line with the idea of less resources needed for the training group to perform this task. *Time frame of the N300*. Supporting the findings from the analyses of the N300 the source localization revealed that the control group needs further resources to successfully differentiate between the ongoing and prospective targets than the training group. For prospective trials the activation was manifested bilaterally in the superior frontal gyrus (BA 10) and for target trials the activation was more dorsal in the left middle frontal gyrus (BA 9,8). In the non-target condition no significant group difference was found. In prospective memory literature prefrontal activations – especially bilateral activation of the Brodman are 10 – have been associated with monitoring processes and a general state of watchfulness (Burgess et al., 2001; Nyberg et al., 1995). Consistently previous results found a higher activation for older adults in the BA 10 compared to young adults during the time window of the N300 (Zöllig et al., 2007). The left middle prefrontal activation found in target trials might for one be specific for the n-back task and for the other display processes going on to maintain the prospective intention. As groups differed in neither of the ongoing variables (only a trend in correct non-target trials) and no interaction with task costs emerged the latter possibility seems more probable. This suggestion is also supported by findings from the prospective memory literature associating activations in this area with maintenance of the intention (Okuda et al., 1998). Recent evidence has led to the formulation of a gateway hypothesis stating that prefrontal areas (mainly BA 10) allocate attention between externally presented information used to detect the occurrence of a prospective cue (more medial regions) and internal thought processes related to the stored prospective intention (more lateral regions, Burgess et al., 2005; Gilbert, Frith, & Burgess, 2005; Simons et al., 2006). As implied by the ERP findings it seems, therefore, that the control group needs more resources to reconcile the present stimulus with the encoded one to decide which target is present and correctly react to it.

For the time window of the *FSW / PP* we found two activation differences in correct prospective trials between the training and control group that seem to underlie different processes. The first seems to be associated with the PP and displayed a clearly higher bilateral activation in the precuneus and cingulate gyrus for the control group. The

second activation difference emerged in the left inferior frontal gyrus (BA 45) and seems to be associated with the FSW. In previous research of prospective memory the activation in posterior regions was associated with the maintenance of the prospective response (Burgess et al., 2001; den Ouden et al., 2005) and was previously found to be higher in adolescents than young adults (Zöllig et al., 2007). Outside the prospective memory literature in studies focusing on episodic memory activation in these regions have been linked with functions related to retrieval of stored mnemonic information (e.g., recollection, retrieval confidence, and imagery, for a review see Wagner et al., 2005). Our results, therefore, imply that the control group might have to rely more on resources associated with the imagining and maintaining of the required response than the training group to successfully perform the prospective task. It might be that the training group formed more elaborate cue-intention-action associations, something that old adults normally are weaker in than young ones (West et al., 2003a). The higher activation of the control group in the left inferior frontal gyrus in correct prospective trials might be related to findings from Simons, Scholvinck, Gilbert, Frith, and Burgess (2006) reporting a greater activation in this area when intention retrieval is more demanding. Hence, supporting the hypothesis that the control group needs to put more effort in a successful performance. This frontal activation is similar to the one found in the time window of the N300, but, given that 400 ms are in between these two time points differential processes are supposed to be activated. However, fMRI research is not able to consider the time aspect in this solution and reports associated processes without considering the temporal dynamics. Future studies should, therefore, focus on the temporal dynamics of processes activated and their underlying generators.

From a theoretical perspective our findings might be explained in line with the multiprocess framework of McDaniel and Einstein (2000) suggesting that our sequence training caused a shift from controlled resource-demanding processing (which put a substantial demand on the strategic allocation of attentional monitoring resources) to more automatic processing. Hence, it could be suspected that the strategies to monitor for the cue vary between groups with the control group monitoring more consciously and strategically. Also the high consistency in the training group suggests that participants might use the same strategy. However, over 85 % of the participants in both groups (N = 17 in each group) have reported that they recognized the cue as soon as they saw it and did not constantly watch out for it. Hence, less than 15 % reported having consciously monitored for the prospective cue and this did not differ between groups. Nevertheless, participants

were only asked two dichotom questions at the end of the experiment, future studies should try to collect this information in a more standardized manner.

What might have supported the automatic monitoring or the feeling of it are the relatively salient colours ‘red’ and ‘blue’. Some participants hinted in the questionnaire at the end of the experiment that the they thought the prospective cues rather salient which had rendered it easier for them to detect. If the cues are chosen less salient the training effect might be even more remarkable as the variability of performance would be bigger.

In summary, our hypothesis that the familiarity with the ongoing sequence might account for the age paradox gets supported by behavioural, ERP, and sLORETA analyses. For a correct performance the control group seems to need more resources to decide which target is present (N300) respectively how to react on it (FSW, PP). Hence, the training group seems to have a specific advantage in prospective memory trails. If this were true, we would have to contradict the age prospective memory paradox as findings are not paradoxical and depending on the task setting but in fact depending on the amount of familiarity with the sequence of events in the ongoing task. As such the distinction of naturalistic versus laboratory tasks seems artificial and not quite touching the point of difference. Hence, future studies should try to evaluate if the opposite is true with old adults performing worse in naturalistic tasks if they are not in their familiar environment and are prevented from doing their habitual every day tasks.

Conclusion

This study focused on the effectiveness of a sequence training to enhance prospective memory performance in old adults and hence, provide a possible explanation for the missing link in the age prospective memory paradox. Our data in all three measurement methods revealed that a benefit for the training group seems supposable: (1) behavioural data showed faster correct prospective reactions and fewer false alarms for the training group, (2) ERP analyses displayed differential patterns for the two groups with the training group resembling young adults and suggesting a higher demand on resources in the control group, (3) source localization distinctively presented group differences in prospective trials with the control group consistently recruiting more resources for a successful performance. Together our data support the hypothesis that the knowledge of the sequence of the ongoing activity might account for the age prospective memory paradox.

4. GENERAL DISCUSSION

In the following chapter the findings from the empirical studies are summarized and their relevance is discussed by relating them to the three presented research questions. For each research area implications are stated and consequences for future studies are discussed. The thesis concludes by adopting a broader view on delayed intentional behaviour and suggesting a unifying model comprising a multitude of factors and processes potentially influencing it.

4.1 Summary and discussion of results

4.1.1 There are neural and behavioural differences in the realization of delayed intentions across the lifespan

The first aim of the present thesis was to increase the knowledge about processes contributing to the previously described 'rise and fall' of prospective memory performance across the lifespan – with a focus on the retrieval phase as the majority of research (for theoretical approaches see Kliegel et al., 2008a; Maylor et al., 2002a). As the involved processes are often assigned to either the prospective or retrospective component of prospective memory our paradigm was designed so as to allow a distinction between these two components. However, our focus lay not only on differences in behavioural measures (i.e., error patterns) but also in differential neural correlates supporting a successful retrieval of a delayed intention (i.e., extra resources needed at both ends of the lifespan to achieve a correct performance). The aim was met by testing three age groups (adolescents, young adults, and old adults) in the same paradigm and combining different methodological approaches (i.e., behavioural data, ERP analyses and their source localization).

Results confirm the previously suggested inverted U-shaped function in performance across the lifespan with adolescents and old adults realizing fewer intentions successfully compared to young adults. Furthermore, our findings support the hypothesis that this developmental pattern does not result from a unitary process across the lifespan. Both methodological approaches (i.e., behavioural and neurophysiological) consistently

found differential age-related patterns in the efficiency of processes associated with the prospective respectively retrospective component.

Regarding the prospective component. Behavioural data suggest that processes associated with the prospective component might be functionally intact by the time individuals reach adolescence while they seem compromised in later adulthood – resulting in a high number of prospective misses (West & Craik, 2001). Consistently, ERP analyses (including PLS results) indicate that adolescents and old adults differentially expressed the N300 and seemed to differ in their way to monitor for the occurrence of the prospective cue. This was supported by source localization data (LORETA) revealing that old adults activated more resources in right prefrontal areas (BA 10) during the time window of the N300 compared to young adults. Functionally, this activation seems consistent with the gateway hypothesis of prospective memory suggesting more resources needed in old adults for cue monitoring respectively comparing the currently presented cue with the previously encoded one (Burgess et al., 2001; Simons et al., 2006). Moreover, older adults showed a bilateral reduction in activity in the cingulate gyrus and medial frontal gyrus compared to young adults in all conditions. This might reflect a reduction in preparation and readiness for actions (Cunnington et al., 2006), which is in line with recent findings suggesting an age-related decline in the recruitment of attentional processes that facilitate cue detection (Smith & Bayen, 2004, 2006; West & Bowry, 2005). Nevertheless, old adults are capable of successfully performing the task. Hence, it seems possible that this generally reduced attentional effectiveness in old adults might have been compensated by the higher prefrontal activation.

Regarding the retrospective component. Processes associated with the retrospective component seem compromised in both age groups - in adolescents resulting in more confusion errors (Guajardo & Best, 2000; King, 2005, July; Smith et al., 2006) and in old adults leading to more false alarms (Einstein et al., 1998). Consistently, ERP analyses (including PLS results) indicate that adolescents and old adults differentially expressed the prospective positivity and therefore seem to differ in their way to recruit post-retrieval processes. This was supported by source localization data (LORETA) revealing different patterns of neural recruitment for adolescents and older adults relative to younger adults in successful trials. Adolescents on the one hand seem in need to recruit more resources in right occipito-parietal regions (including precuneus and cuneus) to correctly execute prospective trials than young adults. This activation was associated with the imagining and maintaining of the required response (Burgess et al., 2001; den Ouden et al., 2005). Old

adults on the other hand show a reduced bilateral activation of the posterior cingulate in trials where the prospective cue was present but the response needed to be postponed. This suggests that old adults are less efficient or less likely to use this opportunity to retrieve or refresh the prospective response than young adults (Burgess et al., 2000; Wagner et al., 2005). This decline of old adults in the efficiency of processes underlying the retrospective component of prospective memory is, however, inconsistent with recent evidence published by Smith and Bayen (2006) where age-related differences in later adulthood for memory processes underlying prospective memory were not observed.

In summary

Our findings for one confirm the inverted U-shaped function of prospective memory performance across the lifespan and for the other reveal that adolescents and older adults show different patterns of behavioural errors and neural recruitment for successful prospective remembering. This indicates that different processes in the intention retrieval phase may contribute to the 'rise and fall' of delayed intentional behaviour across the lifespan.

Implications

The present results have a strong implication of how we should view and approach developmental research. While the behaviourally measured outcome of fewer correct responses might be the same at both ends of the lifespan, the processes underlying this reduced performance might be different. Hence, from findings on one side of the lifespan it can not be concluded on processes or mechanisms in the other. This is also true for compensational mechanisms supporting a successful performance. Therefore, specific developmental models and possibly different diagnostics and interventions are required that are adapted individually for the needs of each age group.

Future research

Processes contributing to age-related differences

Future studies are needed that differentiate the variation of processes across the lifespan on a more distinct level, i.e. the multitude of processes associated with the prospective component should be considered separately to conclude on their impact for differential development patterns. In this line of reasoning additional work is also needed to complete the understanding of the conditions under which age-related differences in

prospective memory in later adulthood reflect a decrease in the efficiency of the retrospective component.

Taking a longitudinal approach

The present thesis looked at developmental aspects and took a lifespan perspective with the underlying data all deriving from a cross-sectional approach. However, longitudinal data would be needed for a 'true view' on developmental process across the lifespan as the influence of supposed underlying processes can only thus be truly measured (Kliegel et al., 2008a). Furthermore, cross-sectional studies always hold the risk of a confounding influence through cohort differences. By using a longitudinal approach this effect could be controlled for and data would reveal if hitherto existing result pattern would prevail .

4.1.2 Age-related differences already occur during the formation of an intention

Whereas the first research question – like the majority of research in this field – examined the intention retrieval phase of prospective memory, the second research question focused on the initial formation of an intention. This is important, as the phases of prospective remembering are consecutive and progress in each phase is likely to depend on the successful execution of the processes and actions required in the previous phases. Therefore, the aim of the second research question was to examine if age-related differences already occur in neural correlates underlying the formation of a later successfully executed intention. The aim was met by testing three age groups (adolescents, young adults, and old adults) in the same paradigm and applying ERP and source localization analyses – whereof the main analytical focus was on the source localization of identified and relevant ERPs with sLORETA.

Results revealed that age-related differences already occur during the intention formation phase. Moreover, in their comparison with young adults adolescents' and old adults' pattern of activated brain regions was clearly different. More specifically, while adolescents recruited more secondary occipital regions in the time window of 500 – 1200 ms and a maximum around 800 ms. Old adults activated more prefrontal regions in two different time windows: the first between 250 and 350 ms and the second beginning at 700 ms, persisting until 1200 ms and expanding to middle temporal regions.

From a functional perspective, one explanation for the higher activation of adolescents in occipital regions during (successful) encoding might be an increased allocation of visual attention and manipulation of visuospatial information during intentional encoding than young adults. This explanation derives from findings on (successful) encoding in retrospective memory (for a review see Cabeza & Nyberg, 2000; Hofer et al., 2007; Morcom et al., 2003). Another explanation might be that adolescents more than young adults rely on encoding strategies based on the surface rather than the semantic content of the stimuli (e.g., involving visual or phonological processing). This explanation is consistent with findings from studies reporting an Sm effect in parietal and occipital regions when the encoding task is non-semantic (e.g., syllable count Davachi et al., 2001; Otten & Rugg, 2001b). Accordingly, given that this occipital activation emerged relatively late (starting at 500 ms), it seems plausible that it not solely reflects a bottom-up process (early visual processing being sensitive to sensory properties) but also top-down processes which might be modulated by prefrontal regions (general attentional effects and mnestic representations, Hopfinger et al., 2000; Kim & Cabeza, 2007).

The functional significance for activation differences in old adults is also based on findings from retrospective memory research. These findings suggest that lateral prefrontal regions support encoding by general executive and working memory processes – e.g., optimization of encoding through processes of selection, handling, and organisation of parts of the episode or generation of goal-directed signals that modulate processes in posterior sensory and association areas (Duncan & Owen, 2000; Fletcher & Henson, 2001; for a review see Lee et al., 2000). This is in accordance with previous research using event-related fMRI reporting higher activation in anterior prefrontal cortex during encoding that predict later successful retrieval (Morcom et al., 2003; Rypma & D'Esposito, 2003). It seems therefore, that older adults in our study, in order to correctly realize the intention, needed to recruit more frontal resources during the encoding of the intention. A functional explanation for the increased activation in middle temporal regions might be founded on the higher likeliness of old adults to integrate new information into the existing body of knowledge. This hypothesis derives from findings in retrospective memory associating regions of the middle temporal lobe with 'information-binding' processes, i.e., the encoding of a consistent representation of parts of the episode (Bunge et al., 2004; Cohen et al., 1999; for a review see O'Reilly & Rudy, 2001). It might therefore be possible that the higher activation of old adults first in prefrontal regions followed by regions in the medial temporal lobe reflects the integration of to-be remembered material into existing

representations through retrieval of past episodes in the prefrontal cortex and the binding of these information in the medial temporal lobe.

In summary

Our findings reveal that age-related differences in neural correlates already occur during the initial formation of an intention that is later correctly realized. Whereas both adolescents and old adults need more resources for the successful encoding than young adults, they substantially differ in their activation pattern. Therefore, these data complement findings from the first study indicating that the processes contributing to the 'rise and fall' respectively the maintaining of prospective memory performance is not uniform at both ends of the lifespan.

Implications

The present results emphasize that a performance failure is not necessarily a failure of retrieval and vice versa a successful performance is firstly achieved by a successful intention formation. Therefore, research on delayed intentional behaviour should further acknowledge the phasic structure of the construct by focusing more on the impact of processes in the different phases on the final outcome in performance. This has, furthermore, a high practical relevance when considering delayed intentional behaviour in specific groups (e.g., old adults or patient groups). To fully understand impaired or maintained behaviour and hence to correctly diagnose and treat a possible impairment it is indispensable to consider all necessary phases and associated processes.

Future research

A *longitudinal approach* is again needed to truly investigate developmental aspects and draw an actual conclusion about underlying processes (see chapter 4.1.1.).

Encoding of different components of an intention

Our paradigm is based on the analyses of the intention as one mechanism. However, the formation of a future intention in prospective memory research consists of three different components: (1) a to-be remembered action, (2) a situation or time point when this action should be performed (prospective cue), and (3) the encoding of the intent itself (see Ellis, 1996; Ellis & Freeman, 2008). During the intention retrieval phase different processes are associated with the tree components and hence it seems supposable that differential mechanisms are already active during the initial encoding. The paradigm

we used does not take this possibility into account. Future research should, therefore, focus on this distinction by separating the three components of an intention in consecutive encoding situations.

Influence of different encoding strategies

In our study participants had to encode one of two actions (pressing a specific letter key) and one of two cues (target colour). With a deficient encoding of the letter participants still had a 50 % chance to press the right key without explicit knowledge. Successful performance in the prospective task despite incomplete encoding seems therefore possible and this might have had an influence on the ERPs. Future studies on neural correlates of prospective memory encoding will have to further explore this possibility by distinguishing between remember- (strong recollection experience) and know-trials (weaker recollection experience) as it was suggested for episodic memory (Ellis, 1996; Ellis & Freeman, 2008; Kliegel et al., 2008a; Kliegel et al., 2002). Specifically, as findings from the retrospective memory literature reporting modulations of the frontal effect depending on the encoding strategy (Daselaar et al., 2003).

Temporal dynamics of processes and their functional significance

The functional significance of activations in prefrontal and medial temporal regions is based on findings from studies using fMRI which means that the temporal dynamics in the range of milliseconds could not be considered. Given that the two regions (prefrontal and medial temporal) are activated in early and later time windows with approximately 400 ms in between suggests that either different processes or the same processes supporting different functions underlay this activation. Hence, future studies combining the high temporal resolution with a source localization method should further investigate the temporal dynamics of processes associated with the intention formation and their underlying generators.

OVERALL: What we have learned by taking a lifespan perspective

The previously implied inverted U-shaped function of prospective memory performance across the lifespan persisted when the same paradigm was applied in all age groups. Furthermore our results reveal that the mechanisms and processes responsible for this maturing and declining of performance are not directly comparable. Consistently, we also

found that compensational neural mechanisms (in different phases of prospective memory) underlying a successful execution of delayed intentions are different in both ends of the lifespan. Generally, this compensational activity is in line with morphological differences across the lifespan suggesting a reduced input of frontal regions in both age groups but differential possibilities to compensate this (e.g., Lenroot & Giedd, 2006; Raz et al., 2005; Raz & Rodrigue, 2006). Old adults on the one hand consistently revealed more frontal activation compared to young adults. This is in line with research reporting a specific compensatory effect of old adults consisting of the recruitment of homologous brain areas mainly in prefrontal areas – the so-called HAROLD-model of aging (i.e., hemispheric asymmetry reduction in old adults, e.g., Cabeza, 2002). However, as we only looked at significant differences between the two groups, further research is needed to investigate if the underlying function shows a reduced asymmetry in old adults respectively if it consistently is lateralized in young adults. Adolescents on the other hand seemed to compensate the reduced frontal input by recruiting further resources from occipito-parietal regions.

4.1.3 Familiarity with the ongoing sequence accounts for the age prospective memory paradox

The third aim of the present thesis was the evaluation of a new explanation that might account for the age prospective memory paradox. More specifically, the explanation that older adults profit in naturalistic settings from a lower need for resource recruitment due to their familiarity with the sequence of stimuli in which the prospective task is embedded. In everyday life this would be comparable to a standard bus ride in which the sequence of stops is well-known although the exact timing and likelihood of a target cue for a particular intention may vary. The aim was met by developing a paradigm that allowed the learning of sequences of events in a laboratory setting and applying it in a between-subjects design (one control group and one training group). The paradigm consisted of a prospective task embedded in a 2-back working memory ongoing task – resulting in target and non-target trials. Different methodological approaches were combined so as to allow a differentiation of the two groups on a performance level (behavioural data) as well as on a compensational level (different resources needed for a successful performance).

Behavioural data revealed that our intervention resulted in a specific advantage of the training group in the execution of the prospective memory task. The specific effect was implied by the fact that all ongoing measures and the analyses of task costs were not

significant between groups. The intervention rather lead to a more reliable and faster prospective cue detection in the training group – revealed by fewer false prospective alarms and faster correct prospective reactions. Although the training group had a higher amount of correct prospective reactions and showed a high intra-group consistency of responding, the two groups were not significantly different.

The more reliable cue differentiation and detection in the training group is supported by findings from the analyses of the N300. Whereas the training group had an elevated amplitude in prospective trials and clearly differentiated these trials from target trials, the control group's amplitude was reduced and did not differentiate between the two trials. Strikingly different was also the topography with the training group's topography resembling young adults' and the control group's being comparable to untrained old adults' (West & Covell, 2001). While this might suggest that the control group has difficulties in differentiating between ongoing and prospective targets, they seem able to recruit compensational mechanisms as all trials considered for ERP analyses are correctly performed. Consistently, the source localization data revealed for one that the control group had in both trials a higher activation than the training group and for the other that the neural pattern differed between trials. Functionally, the higher activation of the control group in prospective trials (bilaterally in the superior frontal gyrus) might be associated with monitoring processes and a general state of watchfulness (Burgess et al., 2001; Nyberg et al., 1995). Again this is similar to the pattern of untrained old adults compared to young adults – see results from the first study in the present thesis reporting a higher activation for older adults in this region compared to young adults during the time window of the N300. The higher activation in target trials (left middle frontal gyrus) might be associated with the maintenance of the intention (Okuda et al., 1998). These findings seem to suggest that the control group needs more resources to reconcile the present stimulus with the encoded one to decide which target is present and correctly react to it.

Regarding both the ERP analyses of the FSW and the prospective positivity the picture was unclear. Findings from the FSW on the one hand were opposite than expected with the control group revealing a higher amplitude than the training group and thus resembling the pattern of young adults (West et al., 2003a). Findings from the prospective positivity on the other hand revealed no differences between groups. It was, however, expected that the control group would need to recruit more resources associated with the two components to successfully perform the task. To explain these unexpected patterns it has to be taken into account that the two slow waves emerged in the same time window –

suggesting that processes are simultaneously activated and might have led to a signal overlap. The localization of sources in this time window was indeed able to distinguish the influence of the two components respectively associated processes by identifying two regions being significantly different between groups. The first region comprised the precuneus and cingulate gyurs bilaterally and revealed a higher activation in the control group which might reflect the prospective positivity. Functionally, these results imply that the control group might have to rely more on resources associated with the imagining and maintaining of the required response than the training group to successfully perform the prospective task (Burgess et al., 2001; den Ouden et al., 2005; Wagner et al., 2005; West et al., 2003a). The effectiveness of the training might be explained by the training group forming more elaborate cue-intention-action associations, something that old adults normally are weaker in than young ones (e.g. Kounios et al., 2001; Sanquist et al., 1980; Weyerts et al., 1997). The second region comprised the left inferior frontal gyrus and revealed again a higher activation in the control group which might reflect the FSW. Functionally, greater activation in this area was reported when intention retrieval is more demanding (Simons et al., 2006) supporting the hypothesis that the control group needs to put more effort in a successful performance.

From a theoretical perspective our findings might be explained in line with the multiprocess framework of McDaniel and Einstein (2000) suggesting that our sequence training caused a shift from controlled resource-demanding processing (which put a substantial demand on the strategic allocation of attentional monitoring resources) to more automatic processing. Hence, it could be suspected that the strategies to monitor for the cue vary between groups with the control group monitoring more consciously and strategically. Also the high consistency in the training group suggests that participants might use the same strategy. However, over 85 % of the participants in both groups (N = 17 in each group) have reported that they recognized the cue as soon as they saw it and did not constantly watch out for it. Hence, less than 15 % reported having consciously monitored for the prospective cue and this did not differ between groups. Nevertheless, participants were only asked two dichotom questions at the end of the experiment, future studies should try to collect this information in a more standardized manner.

In summary

Our data revealed that if old adults are given the chance to familiarize with the sequence of events in which a prospective task is embedded they can increase their performance and

reduce resource recruitment in a laboratory based prospective memory task. Hence, the knowledge of the sequence of the ongoing activity might account for the age prospective memory paradox.

Implications

From a theoretical point of view our findings are important as they imply that the inconsistency in findings of age effects in prospective memory might not be paradoxical at all. They rather seem determined by the amount of familiarity with the ongoing sequence. Hence, the artificial distinction in naturalistic and laboratory-based task settings might be abandoned in favour of the familiarity construct.

From a methodological point of view it is important to notice that slow-wave ERPs can be hard to detect (e.g., time course can be jittered or different generators are active at the same time leading to an overlap of signals) and the absence of significant effects in detecting the slow wave or group differences does hence not necessarily mean that this ERP or difference is not present (for a similar problem see the second study of the present thesis and Gutchess et al., 2007). It is now important to notice that a source localization method can help to disentangle the overlapping input and reveal the possibly different underlying generators. Furthermore, our data imply that it is not possible to conclude on the effectiveness of underlying functions by solely looking at the amplitude heights (i.e., higher amplitude means better functionality). Again, a source localization analyses can reveal further information in this point by calculating activation differences between groups or conditions.

From a practical point of view our findings have a high relevance as a basis for interventions as they implicate that a high familiarity with the sequence of daily activities facilitates the correct realization of delayed intentions. It might therefore be possible to use this efficient mechanism of old adults in situations where the familiarity of daily routines is poor by increasing the amount of familiarity through external interventions – like for example when relocating to a nursing home.

Future research

Effect of a more intensive intervention in a within-subjects design

Remember that although the training group had a higher mean of correct prospective reactions and showed a high intra-group consistency of responding, the two groups were not significantly different. This might be explained by the relatively short

duration of the training (a mean of 45 min) and the possibly restricted effect of it as only one of two aspects of the sequence were learned to completeness (only information of position and not colour was learned to criteria). Hence, a more intensive training with the learning of all information of the sequence might achieve a significant difference in correct prospective trials and further enhance its effectiveness. Furthermore, the training should be applied in a within-subjects design comparing results to a wait list control group to consequently ascribe the effects on prospective memory performance to this intervention.

Explanations for the age benefit

Explanations for the sometimes reported age *benefit* (better performance of old adults compared to young adults) can not be given with the current data. It is, however, possible that the prospective task in naturalistic settings depend mostly on automatic processes (reducing strategic demands and therefore the age effects, see multiprocess framework of McDaniel and Einstein, 2000) and that young and old adults have hence the same starting position. If now differences in the aforementioned variables (see chapter 3.3.1.) like motivation or effectiveness of external memory aids between age groups systematically occur it might explain the age benefit. However, future research is needed to test the multiprocess framework in real life and study interactions with variables like motivation and external memory aids.

OVERALL: What we have learned by combining methodological approaches

Our findings imply that the combination of methodological approaches is an important advance to extend the developmental view of prospective memory and illuminate associated processes and mechanisms underlying the reduced but also the maintained performance. Additional research is now needed to further investigate differential patterns in behavioural outcomes, temporal dynamics of processes, and the underlying neural generators – both between age groups but also between conditions in one age group.

It is especially important to underline the value of investigating mechanisms and processes leading to successful performance. Findings from all three studies have shown that whereas the performance outcome might be the same, underlying processes and activations might be fundamentally different. Hence, by focusing on stable performance and how this can be maintained (associated processes and structures) we gain a

fundamental basis for building interventions respectively targeting declines. Consistently, it provides a mean to measure compensation – and this in a time range of milliseconds.

Furthermore, our results imply that by including source localization in ERP analyses possible methodological difficulties (e.g., component overlap, functional significance of amplitude height) can be solved. Whereas the inclusion of ERP analyses helps to define a time window of interest to perform a source localization differentiating groups or conditions respectively indicating where interesting differences in neural generators might occur.

4.2 Outlook on a unifying model of delayed intentional behaviour

There is consensus – more or less – on the phases of prospective memory. However, further research is needed to clearly identify different processes needed in specific phases and possible factors influencing them. Hence, the present thesis closes with a suggestion of a unifying model of delayed intentional behaviour by considering the findings from our studies and the consequential thoughts, ideas, and questions as well as by adapting a broader theoretical view. The presented model is far from being exhaustive, however, it provides a basis for taking different perspectives on the construct 'prospective memory' and understanding it in more detail. In a first step factors and processes potentially influencing delayed intentional behaviour are specified and in a second step these factors and processes are applied – as far as possible – to the phasic structure of prospective memory.

4.2.1 Multitude of factors influencing delayed intentional behaviour

The majority of processes and factors which are discussed to play a role in delayed intentional behaviour are cognitive in nature. However, while dealing with the construct 'prospective memory' and integrating our findings in the current literature it got clear that a variety of other factors and processes such as social and personality aspects (including motivational) might play an important role. Furthermore, our findings from the third study imply the importance of environmental aspects for the effectiveness of prospective memory. Hence, the following chapter gives a short insight in a selection of processes and factors potentially influence delayed intentional behaviour by considering the three fields:

(1) cognitive processes, (2) social and personality factors (incl. motivational processes), and (3) environmental factors.

Cognitive processes

Traditionally, researchers in the field of prospective memory focused on the investigation of cognitive factors influencing different processes or tasks (e.g., attention, task shifting, inhibition, etc.). Increasingly, the effort has expended to explore variations between different task designs and their impact of performance as well as the exact processes that are employed in these tasks (e.g., automatic vs more strategic processing resulting in the multiprocess framework of McDaniel and Einstein, 2000). However, as mentioned previously, further research is needed to clearly identify *processes and their temporal dynamics in the different phases of prospective memory*. In this line of reasoning the existing models of prospective memory should be adapted to the phasic structure of the construct (the two most prominent models being: (1) the PAM theory (Smith, 2008; Smith & Bayen, 2004), and (2) the multiprocess framework (McDaniel & Einstein, 2000)). More precisely, the models should specifically state their validity for the processes in each phase. For example, it is not clear in which phase or phases the reduced attentional resources of old adults (reported in the PAM theory) influence the reported repetition errors: Are they resulting from insufficient attentional resources affecting encoding AND/OR are these limited resources impacting the ability to retrieve? Moreover, the effects of *practice and regularity* on cognitive processes influencing performance outcome should be taken into account. An automation of a process might lead to less effortful, spontaneous retrieval which might hence, sustain correct performance. A further most relevant aspect influencing cognitive aspects are *strategies*. Strategies can influence encoding (e.g., implementation intentions leading to deeper encoding) but also the choice of monitoring (e.g., strategic, automatic, familiarity plus search, clock-checking). If we look at encoding of an intention – consisting of action, cue, and intent – it gets clear that especially the last factor ‘intent’ depends also on other factors like the will to perform the intention and the commitment. Hence, the following section discusses factors outside the traditional field of prospective memory researchers but which potentially influence its outcome – namely social and personality factors.

Social and personality factors

To identify processes in this field it seems helpful to include complimentary approaches from social and personality psychology (including also the broader field of intentional behaviour). Social psychologists, for example, have enforced the discussion of *how specific intentions are selected and formed in the first place*. The important question for them is why we decide on one course of an action rather than another in the pursuit of an overarching goal. Reasons might be *external expectations* which might again influence the personal importance of the intention (i.e., what impact has the outcome?) and the motivation to fulfil the intention respectively the degree and type of commitment. As such the decision to act depends not only on the capability but also on the willingness and commitment. In this line of reasoning, also *internal expectations* seem important touching now research form personality psychology. Personal beliefs, for example, can influence the choice of action respectively the degree of commitment and motivation to fulfil the intention. This might be important during encoding of an intention but also in finally executing it – one acts with half knowledge, the other only when he is 100 % sure. People may also differ in their final decision to act respectively the decision if the match between cues is enough or not – individual differences when one is willing to act. One difference might also be the *stress level* differing between persons and which might influence cognitive processes (e.g., during encoding, but also retrieving the exact content). Furthermore, *classic personality traits* like the big five factors might differentially correlate with performance. A systematic investigation whether for example 'conscientiousness' influences performance and in which phase might reveal important findings. Generally, research on personality is based on defining individual differences. This concept should be adapted for research in delayed intentional behaviour and lead to the investigation of mechanisms underlying different performance between individuals in all three presented factors (cognition, personality and social, environment).

Environmental factors

Finally, our findings have revealed how important environmental factors like *familiarity and regularity* might be for a successful performance in delayed intentions. It seems supposable that the effect of familiarity gets effective during the intention retention phase. This is based on the idea that one's activities during a retention interval influence later retrieval success as they may vary in nature (e.g., focal – non-focal to the prospective cue), duration, and number, but also in attentional demands and processing focus (Smith, 2008;

Smith & Bayen, 2004). Besides familiarity and regularity also other characteristics of the environment like *complexity, salience of the cue, and instructions* might influence performance.

Neural correlates could again be used to identify differences between conditions, and groups as well as measuring the influence of different factors. Some examples might be: Do two groups of persons with high and low scores on conscientiousness differ in their neural correlates of correct prospective reactions? Are there differences in activation before and after a training of how to use implementation intentions? Does stress prevent a successful performance through encoding or retrieval of an intention?

4.2.2 The unifying model

The second step now integrates these factors and processes with the phasic structure of prospective memory. Hence, not providing an unalterable model but rather a first suggestion of how these factors and processes might influence the performance outcome of prospective memory.

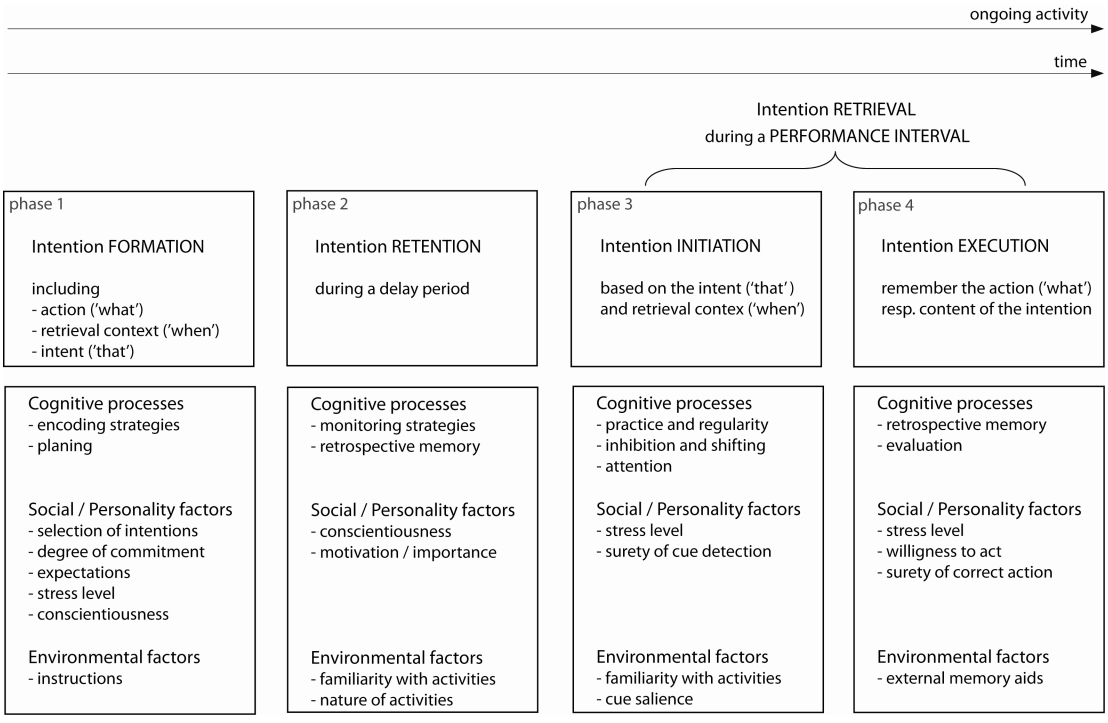

Figure 16. Unifying model of delayed intentional behaviour.

Apply the extended model in developmental populations

In regard to developmental research this model might provide a basis to plan and interpret future research on prospective memory and especially on how we develop, maintain, and sustain the ability to determine and enact intentions at appropriate future moments and what processes underlay a reduced performance. More specifically, it might be applied to investigate the future research questions mentioned above. Findings from such a model would help to determine those components (consisting of processes, factors, and phases) that are most crucially and differentially involved in developmental changes. Particularly, it might provide a basis for explaining how individuals at different ages manage to perform well in prospective tasks that are important to them. That is, how do children learn to perform reasonably accurate in going to school, doing homework and so on. How do middle aged adults perform well in social and work-life and older adults in taking medication. What is the basis for improving this performance (vs error prediction)?

The proposed model has no claim to be exclusive and is mainly based on findings from the present thesis and the consequential thoughts, ideas, and questions. Hence, future research will definitely add or reassign processes and factors in the different phases. However, this model is a first approach to integrate possible factors and processes underlying and influencing the performance outcome of delayed intentional behaviour. And as such it provides an ideal basis to identify, plan, and execute future research and interpret and evaluate their findings.

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CURRICULUM VITAE

Education

2005 – 2008	University of Zurich, Department of Psychology Doctoral candidate
2005 – 2008	Neuroscience Center Zurich International Ph.D. program in neuroscience
2000 – 2004	University of Zurich, Department of Psychology Diploma (Licentiate) in psychology
1998 – 1999	University of Lausanne, Department of Psychology Intermediate diploma (first year) in psychology

Employment History

Since 2005	University of Zurich, Department of Psychology Research assistant
Since 2005	University of Zurich, Department of Psychology Co-leader of the neuropsychological ambulance (driving aptitude and neuropsychological diagnostics)
2001 – 2004	University of Zurich, Department of Psychology Research associate

Awards

2007	Vontobel Award for Research on Age(ing) (endowed by the Vontobel Families Foundation at the yearly Zurich Gerontology Day)
2005	Poster Award (1st rank) (endowed at the 3rd congress for undergraduate and graduate students of the Department of Psychology, University of Zurich, LiDoKo)